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Title: DARHT Axis 1 Pulsed Power and Beam Dynamics Review

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DARHT Axis 1 Pulsed Power and Beam Dynamics Review

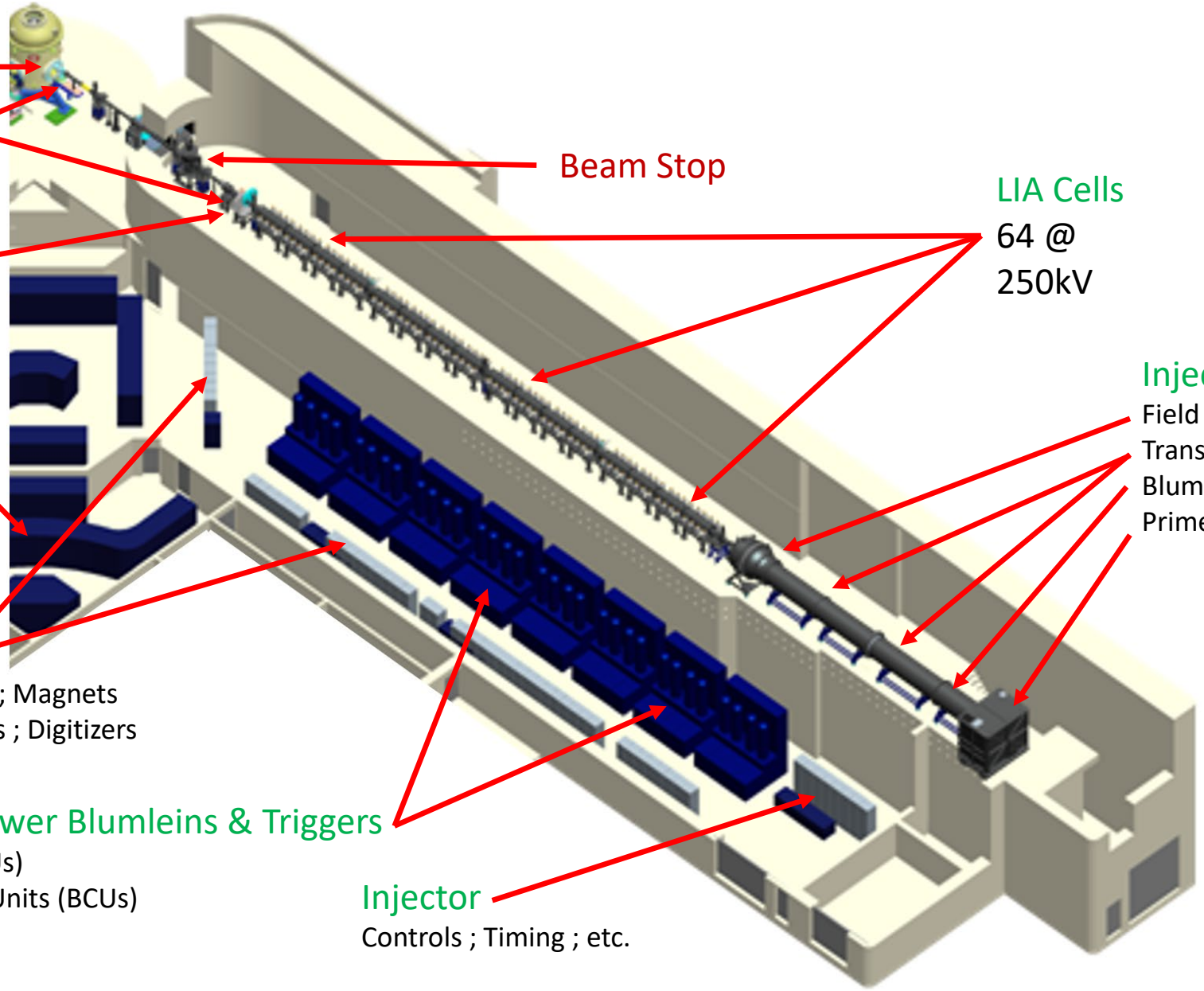
David C. Moir
and
Brian Trent McCuistian

J-6 Engineering Operations and Physics

DARHT Axis 1 System Overview Part 1 (Pulsed Power)

Brian Trent McCuistian

DARHT AXIS 1 OVERVIEW



Converter Target

Downstream Transport
Drift region

Spinning Wheel
(Debris Blocker)

Control Room Console
Accelerator Controls
Data Acquisition & Timing
Data Analysis

Equipment Racks
Controls : PLCs, I/O
Power Supplies : Pulsed Power ; Magnets
Data Acquisition & Timing : DGs ; Digitizers

Cell Pulsed Power Blumleins & Triggers
Trigger Units (BCUs)
Blumlein Charge Units (BCUs)
Blumleins

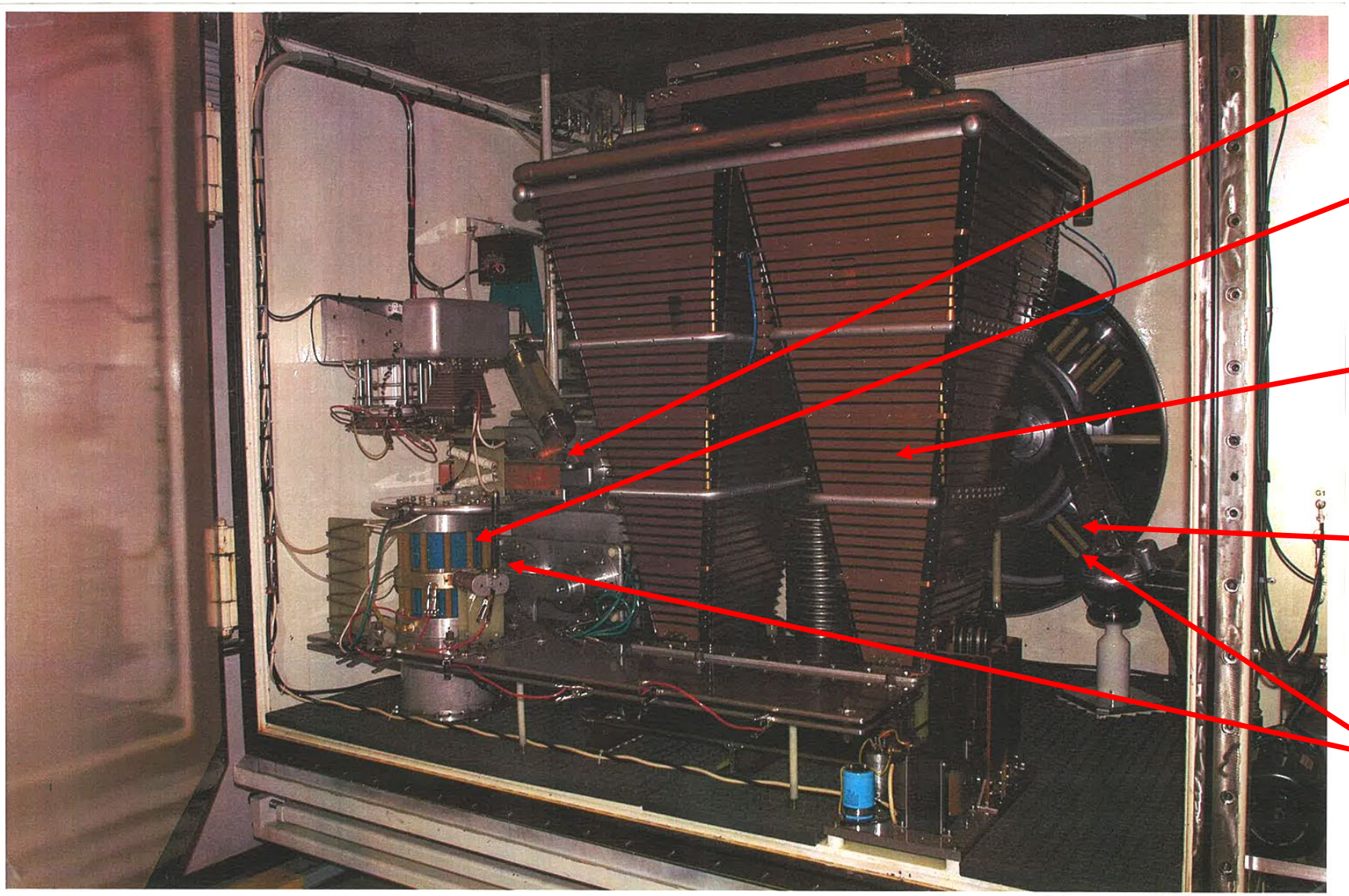
Beam Stop

LIA Cells
64 @
250kV

Injector [4MeV]
Field Emission Diode
Transmission Lines
Blumlein
Prime Power Tank (PPT)

Injector
Controls ; Timing ; etc.

PRIME POWER TANK (PPT)

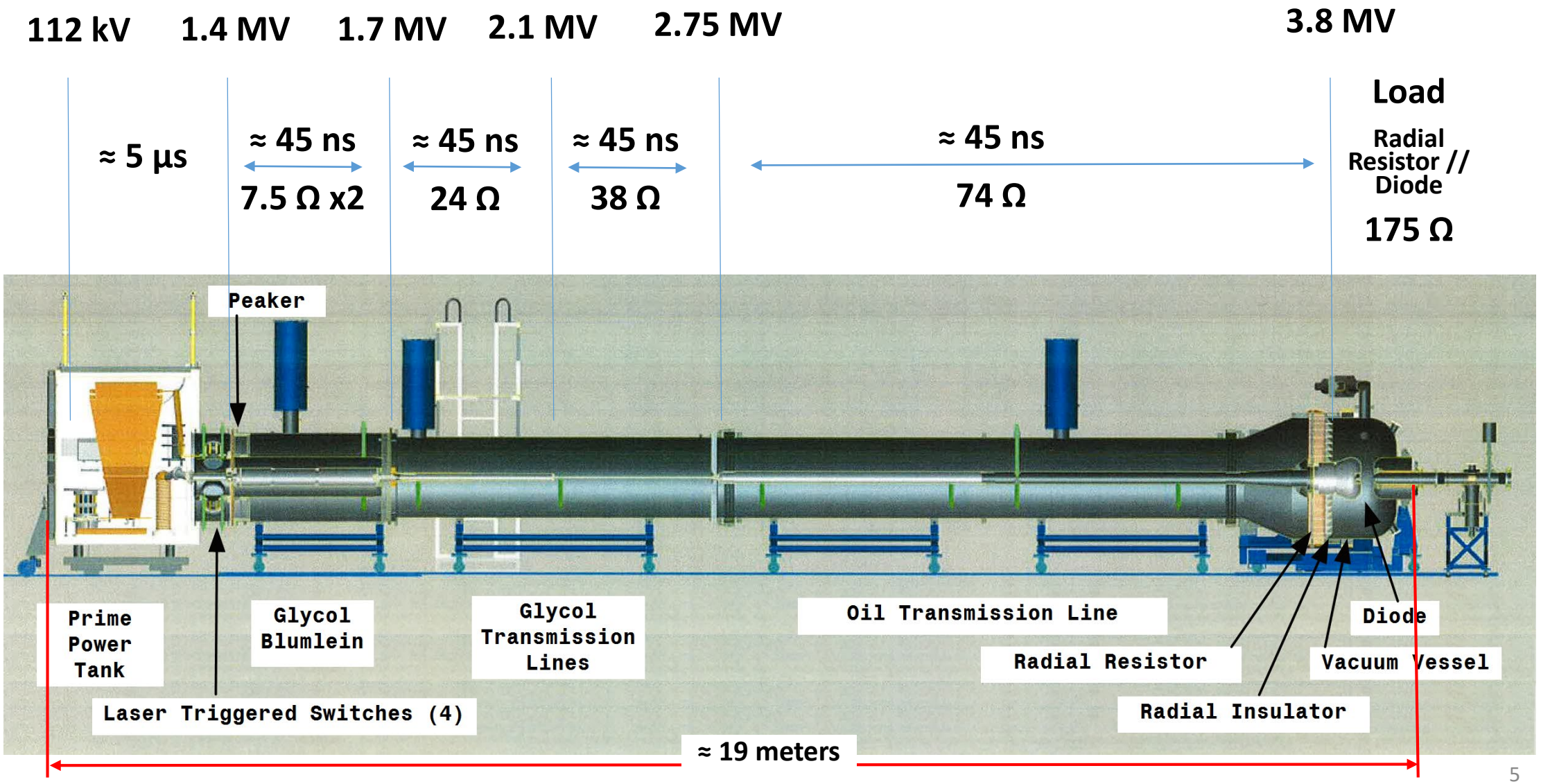


- 3µF charged 112kV
- Air Spark Gap Switch triggered by Thyratron circuit
- Stanganese 1:15 step up XFMR charges (+) Blumlein Intermediate
- 4 Laser Triggered SF_6 Spark Gaps on Blumlein

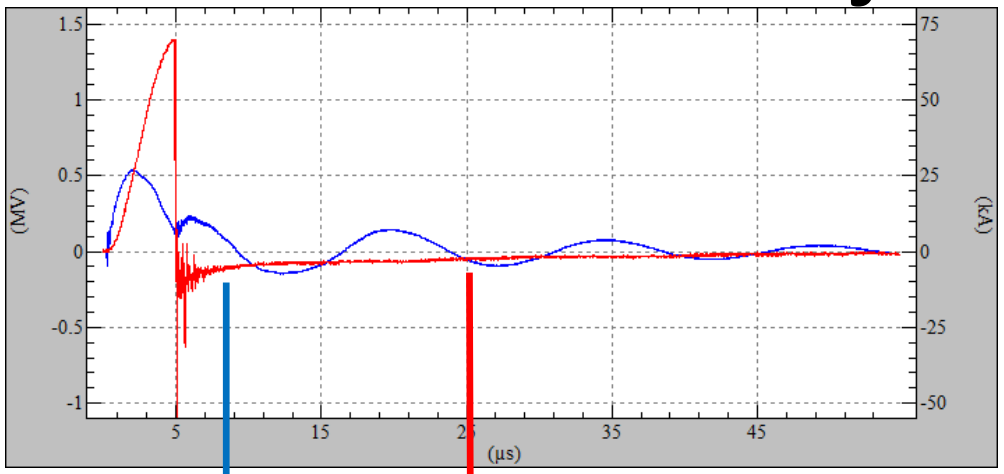
Nd-Yag frequency quadrupled 266nm ; 100mJ out of laser

- Monitor Current through All Switches

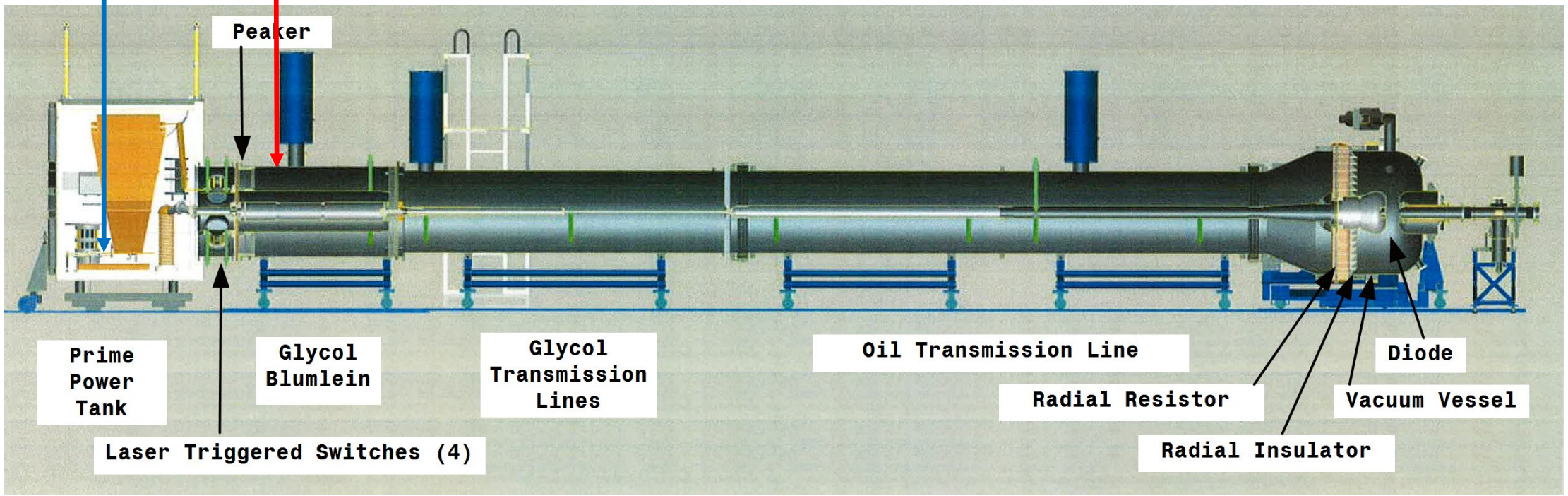
DARHT Axis 1 Injector



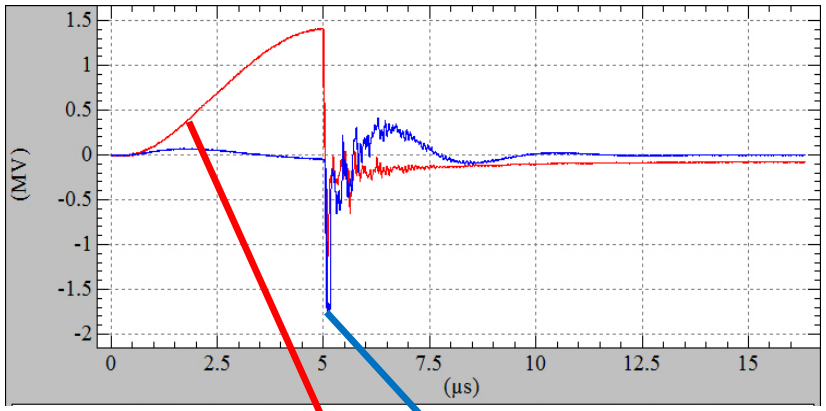
DARHT Axis 1 Injector Pulse Charge Waveforms

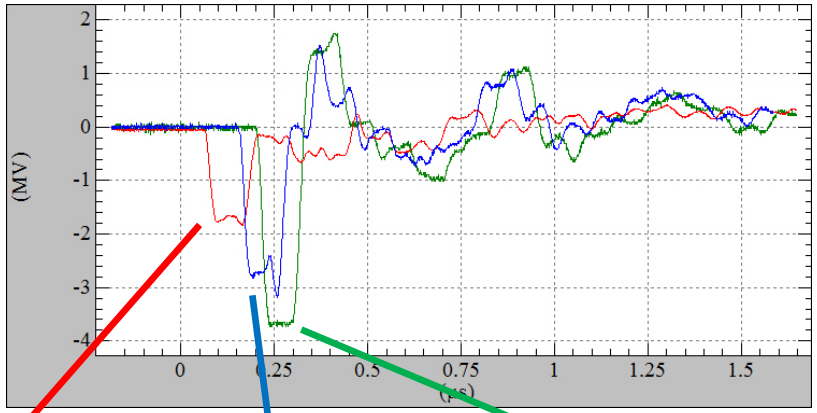


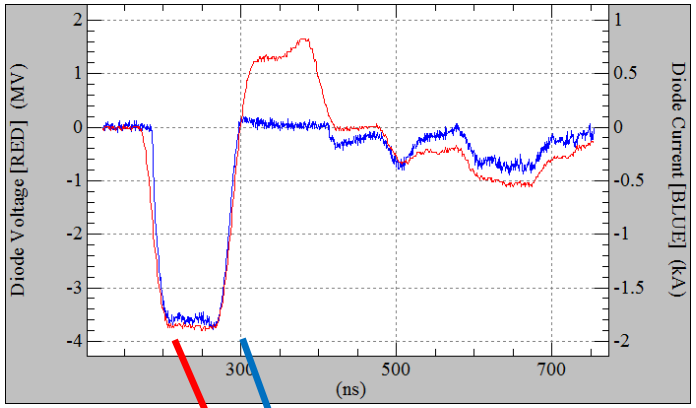
- PPT Primary Current
- Blumlein Charge Voltage

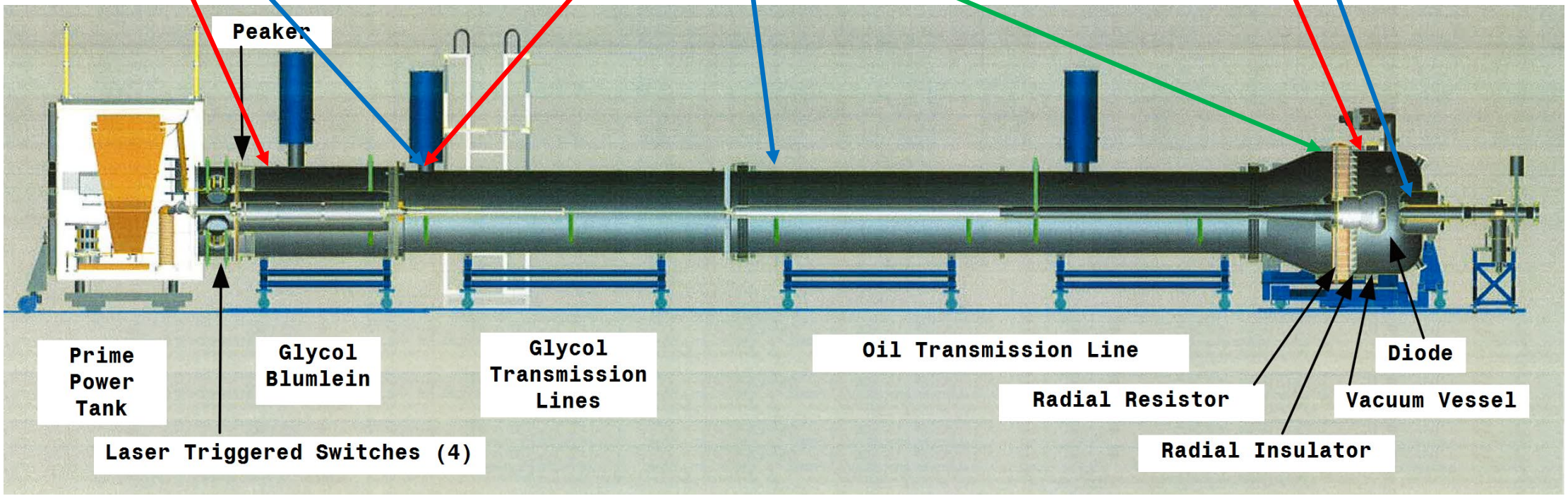


DARHT Axis 1 Injector Voltage Waveforms

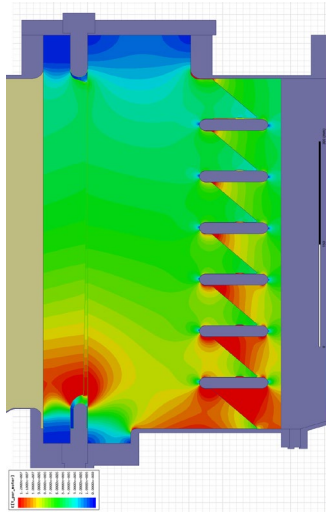








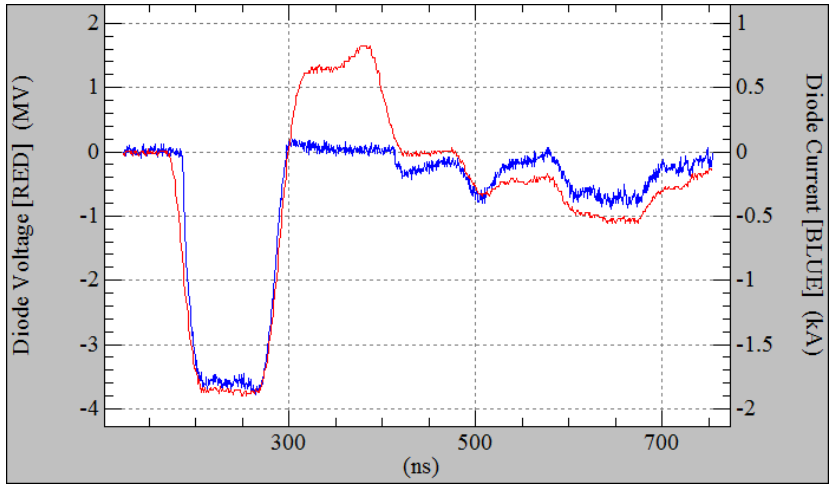
DARHT Axis 1 Diode Region

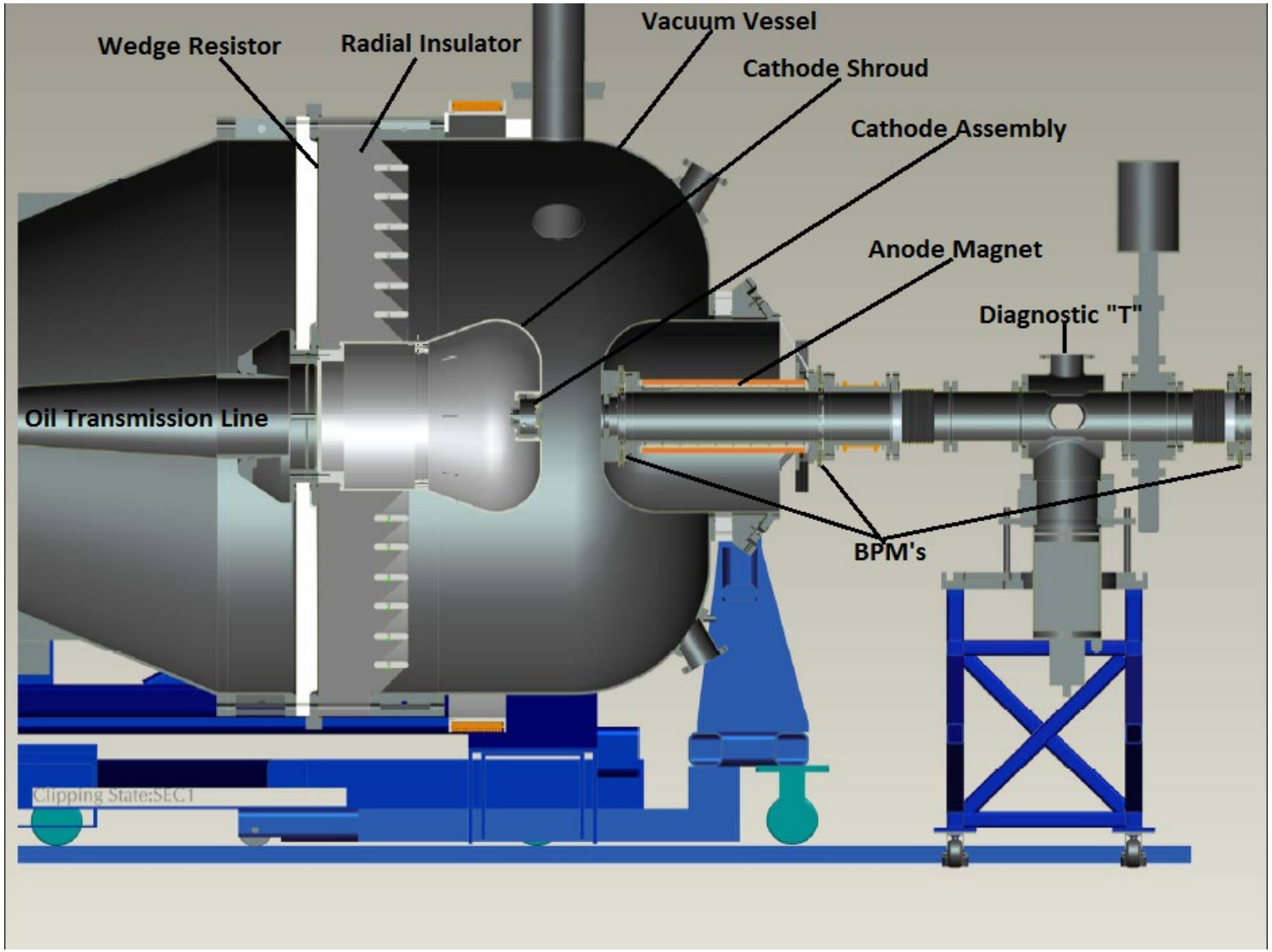


- Diode Voltages:
1.4 MeV to 3.8 MeV

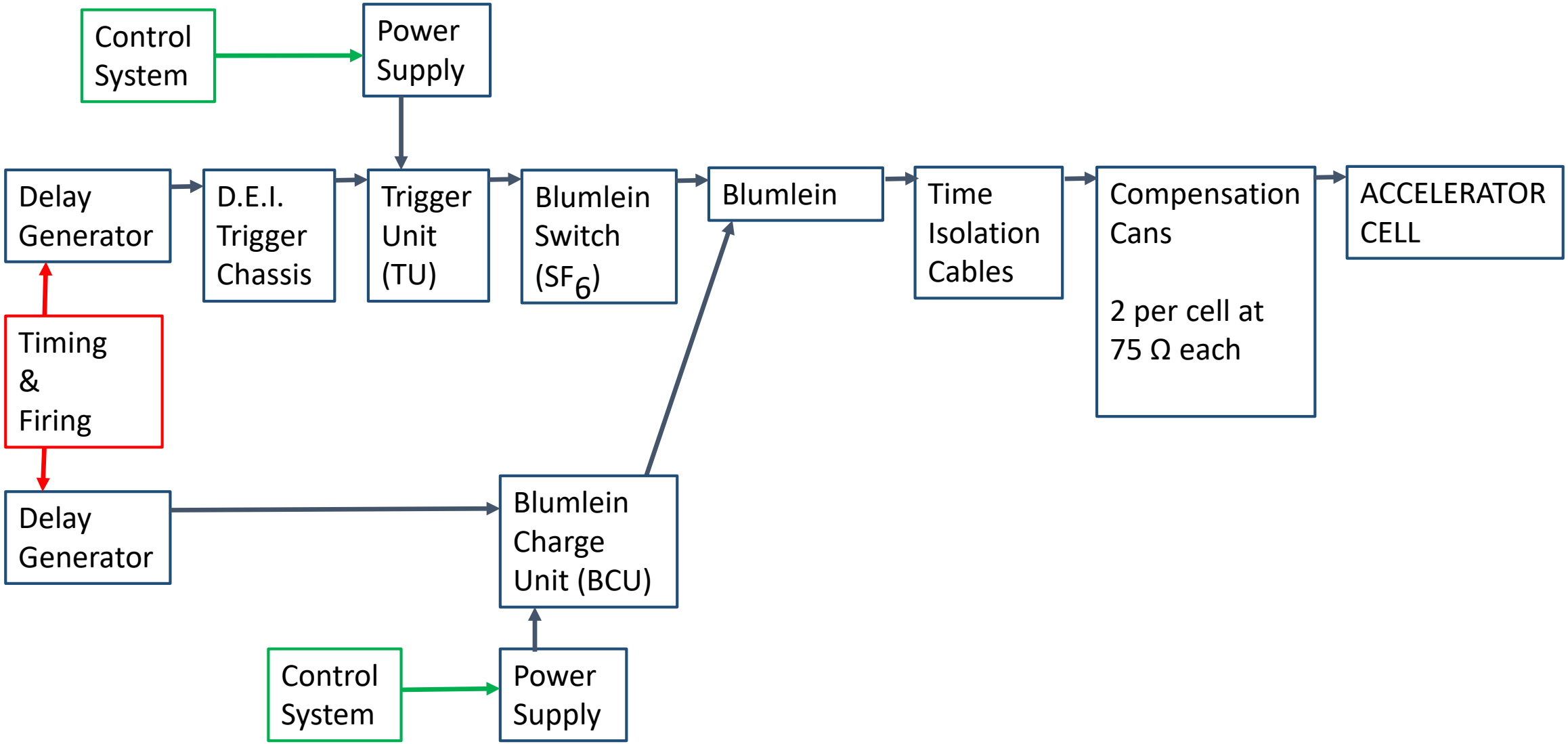
- Cathode Diameters:
70mm, 50mm, 25mm, 19mm

- 112kV charge voltage →3.75MV
- 50mm diameter cathode → 1.8 kA

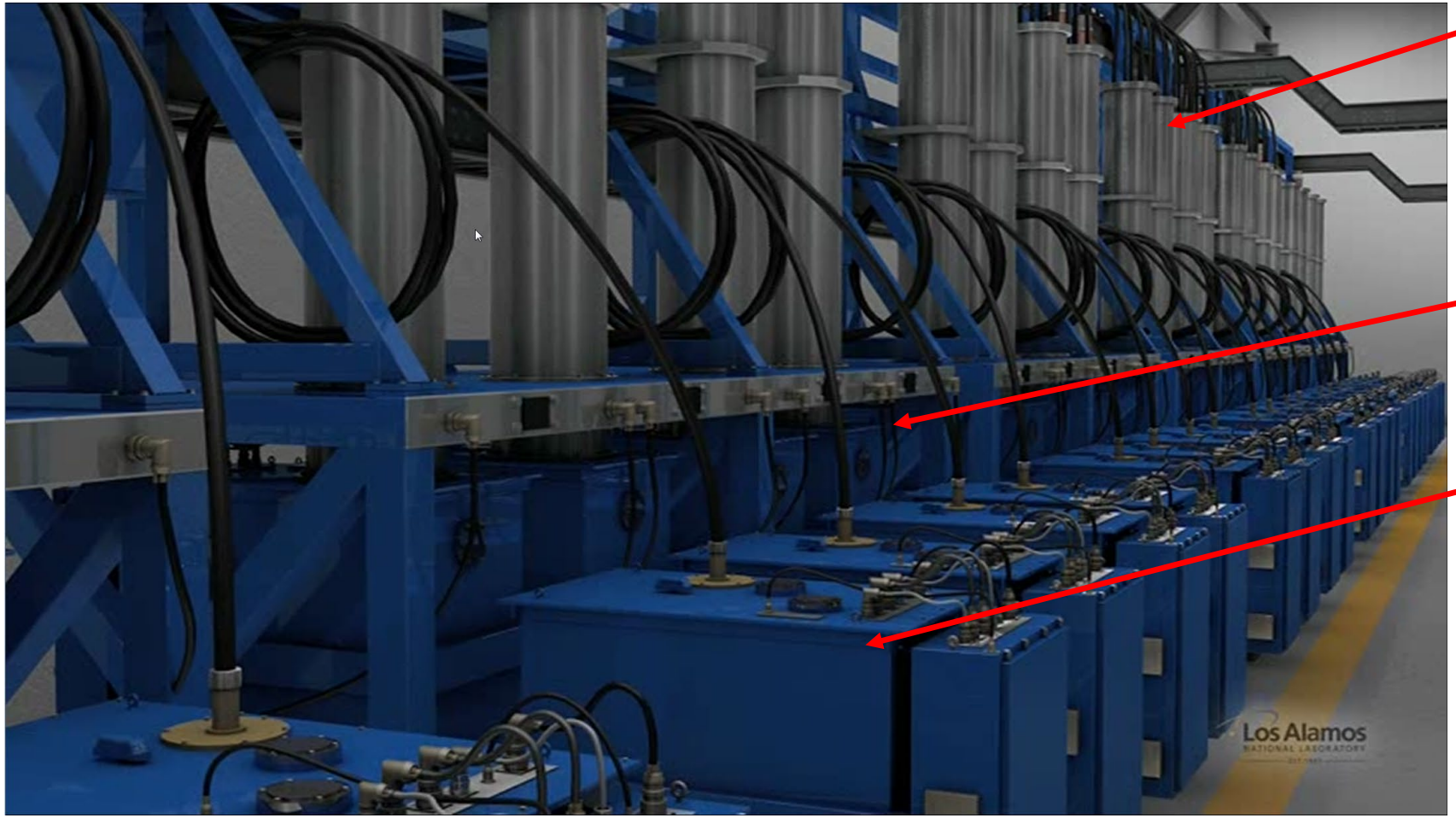




DARHT Axis 1 Cell Pulsed Power Drive Block Diagram



DARHT Axis 1 Cell Pulsed Power



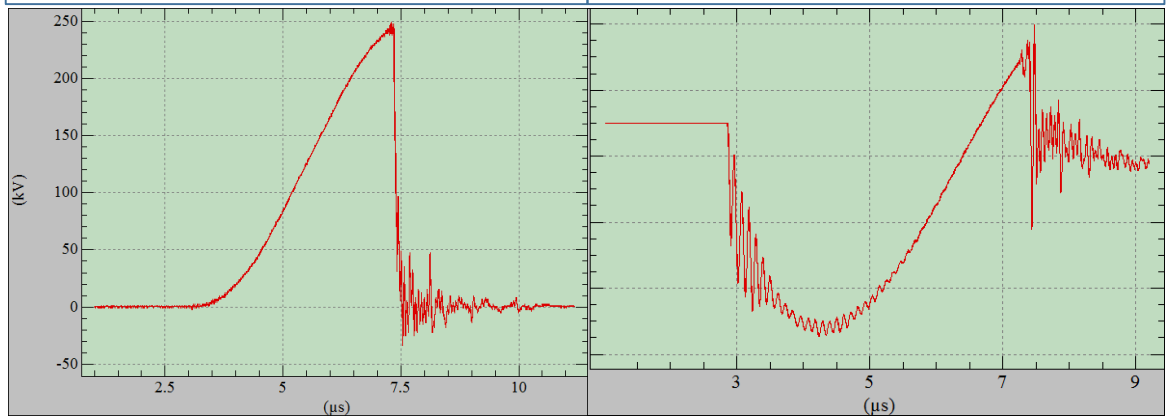
- Blumleins (32 total)
  - Output 4 cables @ 40Ω each
  - 2 cells (2 cables / cell)
- Blumlein Charge Units (BCUs)
- Trigger Units (TUs)
  - Triggers Blumleins

Blumlein Charge Unit (BCU)

Blumlein

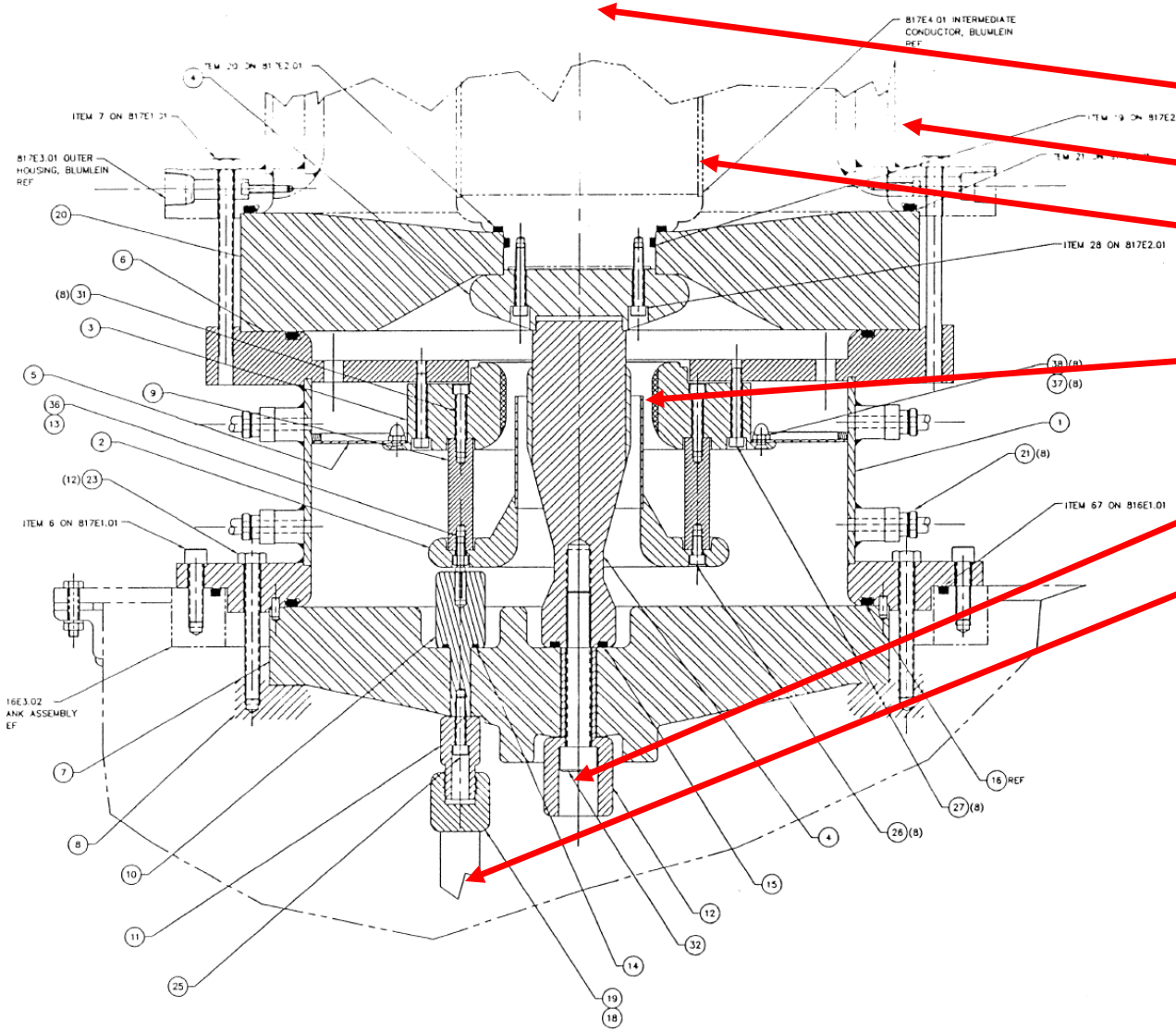
Blumlein Switch

Blumlein Charge Voltage	BCU Thyratron (1) Current



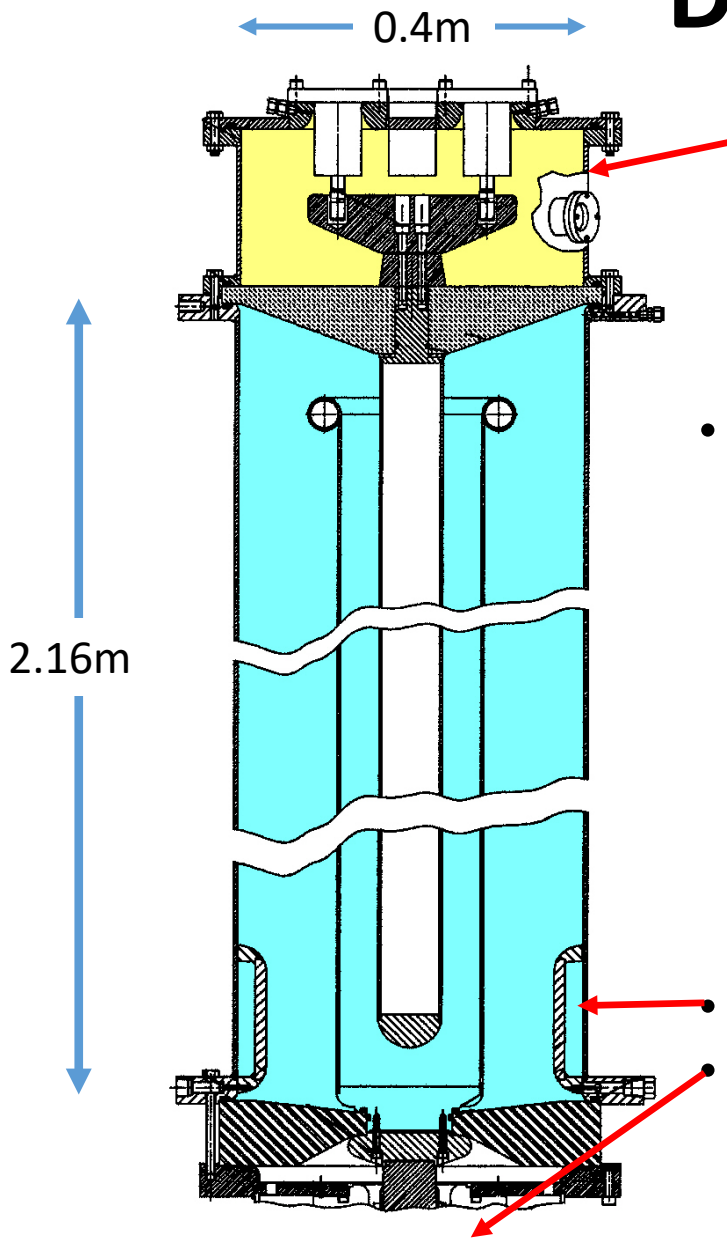
- Two 1.4 µF Capacitors
  Charge Voltage 27kV nominal
- Two Thyratrons (current)
- 1:11 Step Up Transformer
  Two primaries

DARHT Axis 1 Blumlein Switch (SF_6)



- Blumlein Inner (not pictured)
- Blumlein Outer
- Blumlein Intermediate
- Spark Gap
- BCU Charge Pulse
- TU Trigger Pulse

DARHT Axis 1 Blumlein

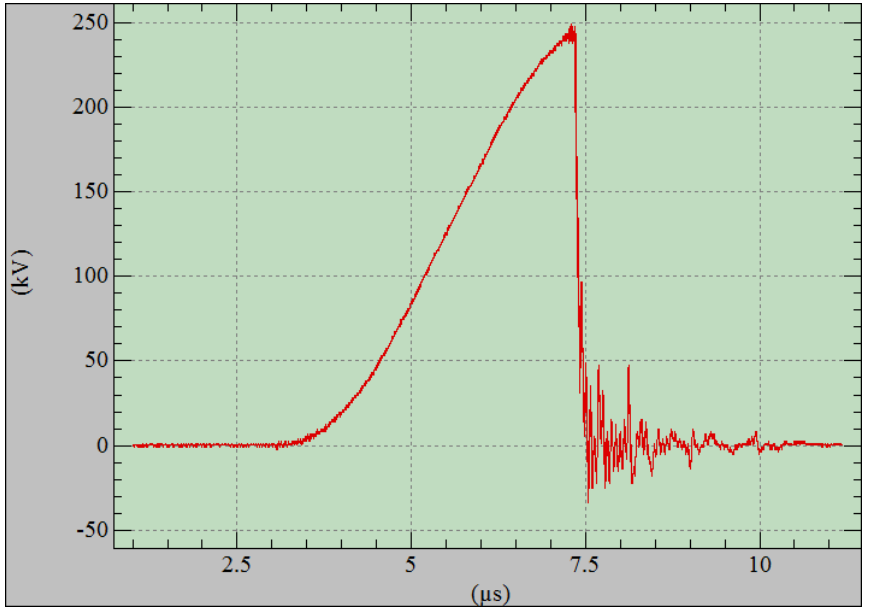


- Oil Filled Header for 4 Cables Feeding Cells
- 106 & 107.5 ns isolation/delay
- Dielectric Sciences 2158 (41Ω)

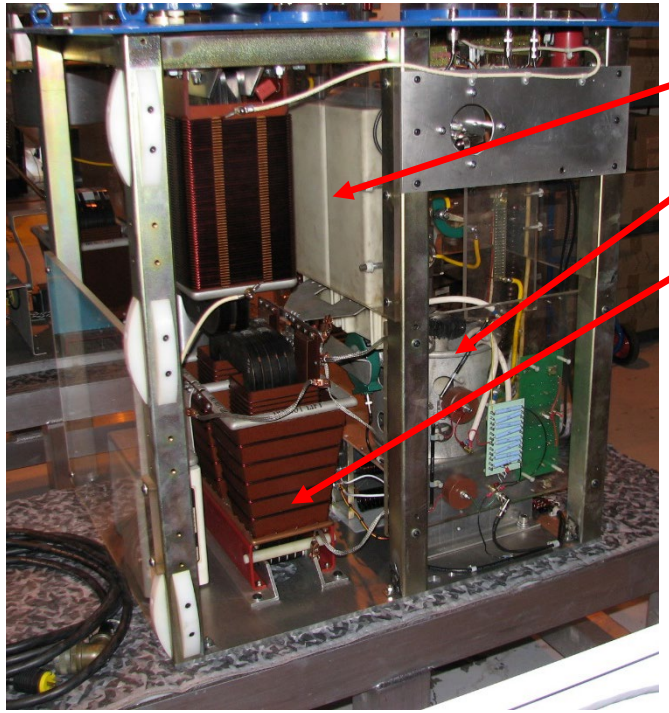
- Blumlein 85 inches tall
  - Inner & outer (each) ≈
    - 10nF
    - 5.8Ω
    - 55ns
  - 70 gallons water
    ≥ 16MΩ

- Peaking Section
- SF6 Switch

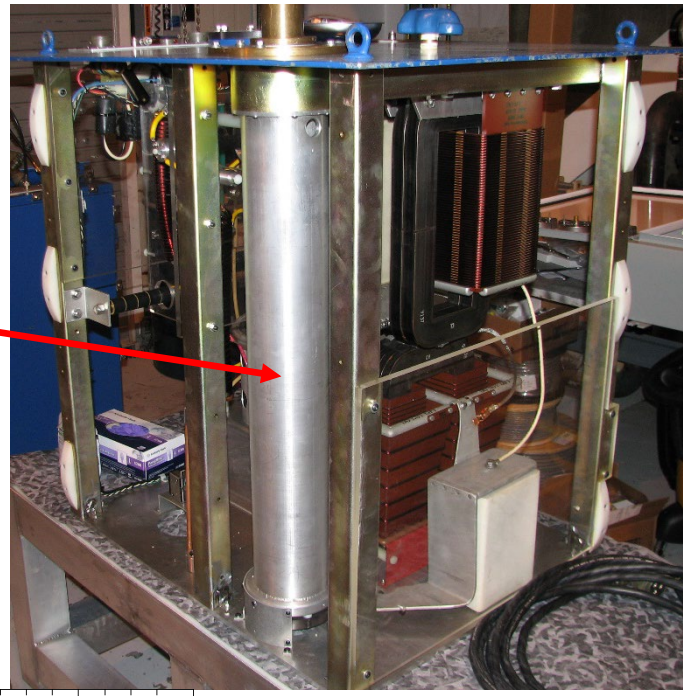
- Pulse Charged
  - ≈ 4.5 µs
  - 250kV

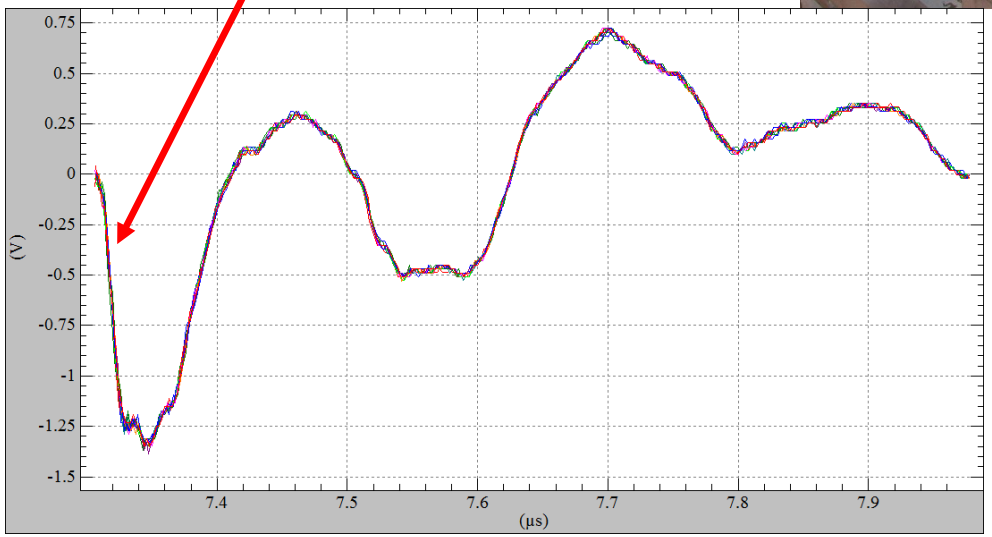


DARHT Axis 1 Trigger Unit (TU)



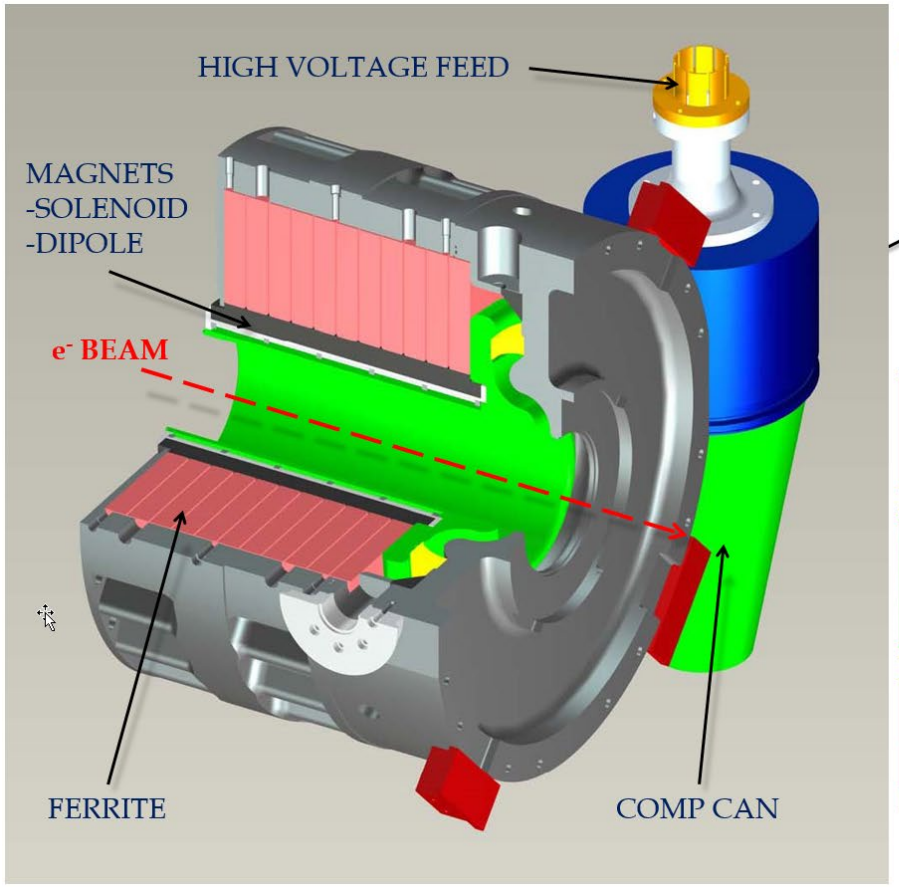
- 60 nF @ 40kV
- Thyratron
- Output Xfmr 1:4
- Shockline (Pulse Sharpener)
- Oil Temperature Regulated for tight control on Jitter ≈2ns

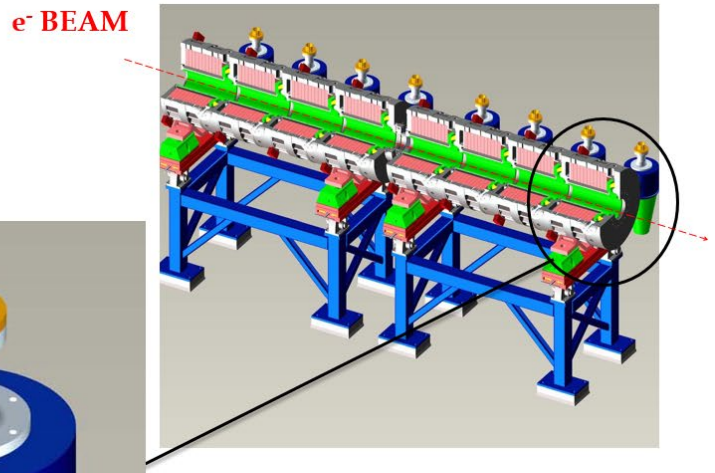




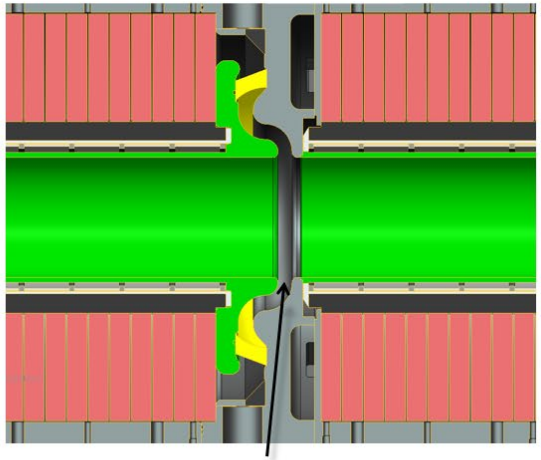
DARHT AXIS I

INDIVIDUAL CELL



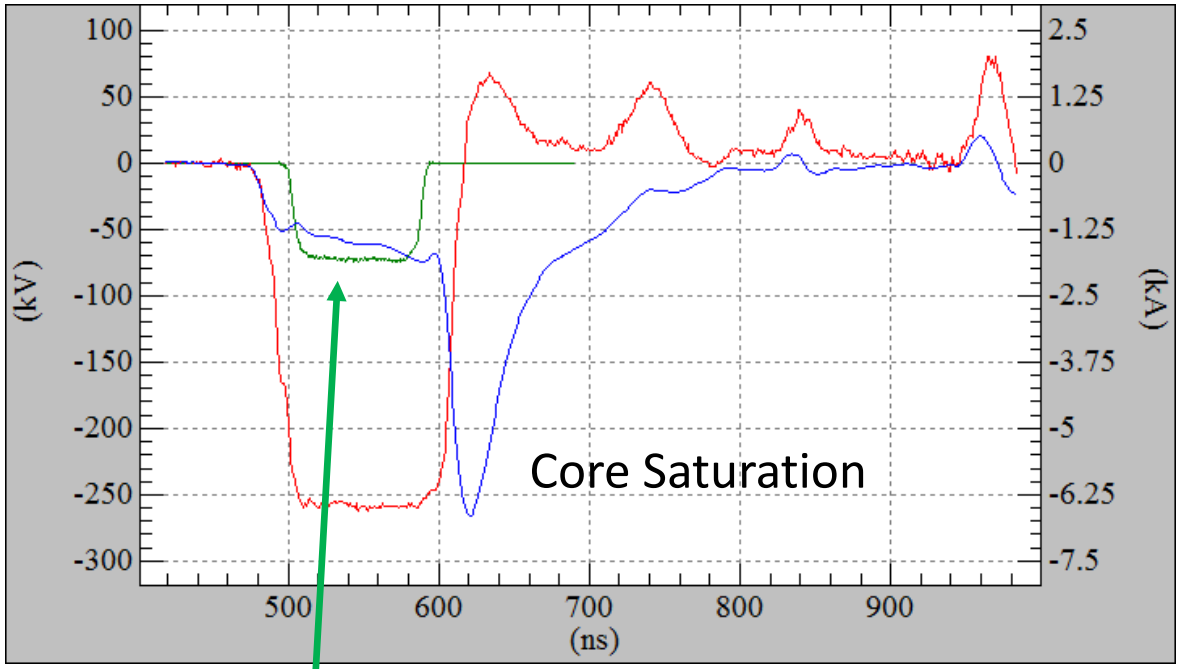


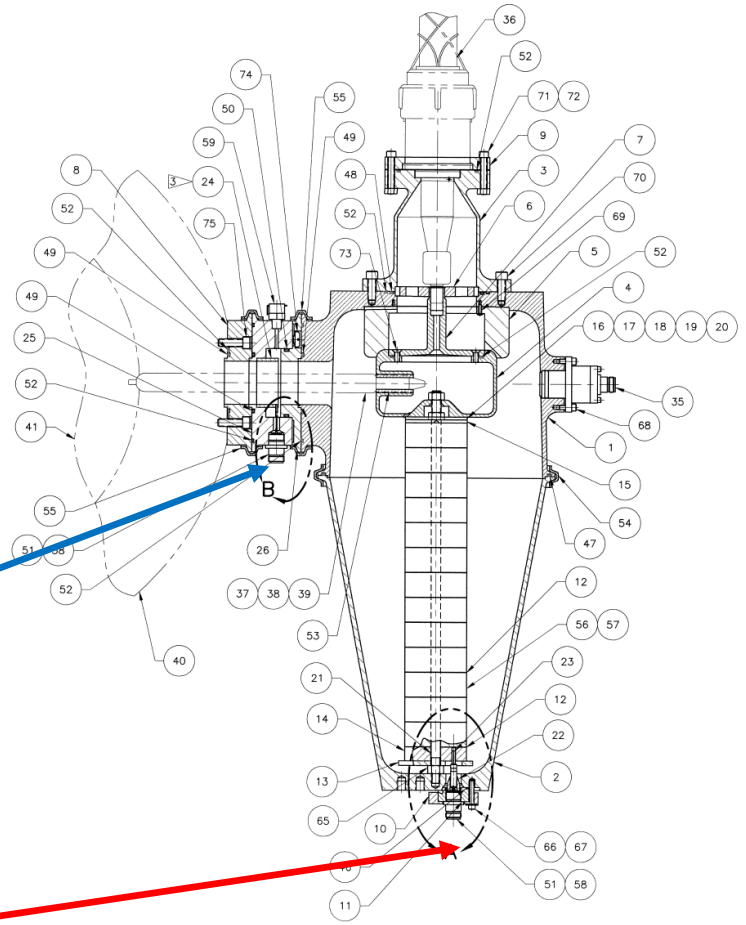
CELL BLOCK ASSEMBLY



- 11 Ferrite Cores / cell at 2.5mV-s (TDK PE16)
- 27 mV-s per cell
- Accelerator Gap holds 250kV pulses reliably (shielded gap)
- Two Compensation Cans 75Ω each per Cell

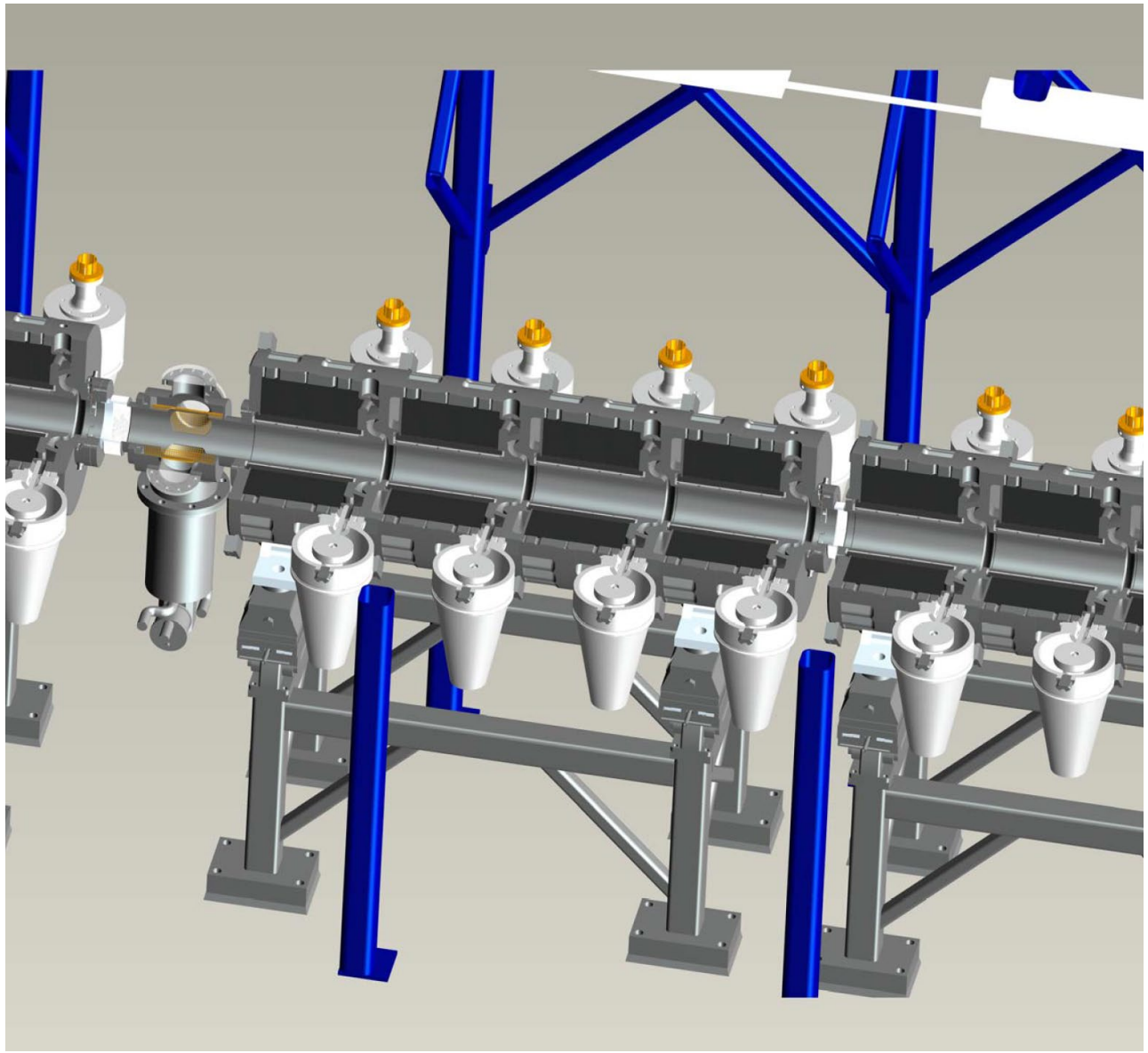
DARHT Axis 1 Cell Compensation Can

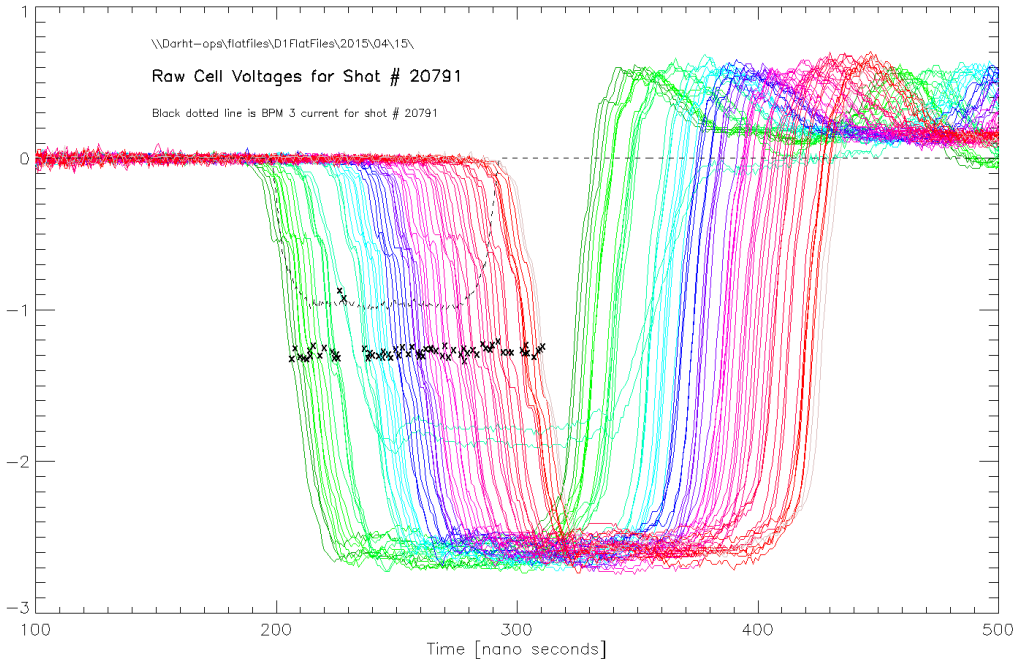




- Beam Current
- Drive Current Bdot
  - Not presently recorded for all cells
- Resistive Cell Voltage Monitor

DARHT Axis 1 Cell Block





- Delta T = measured – ideal cell timing

For last Hydrodynamic Shot:

- Delta T average = -0.16ns
- Delta T Stddev = 1.7 ns

DARHT Axis 1 Liquids

Region	Fluid	Volume Each est.	Total Volume est.
Injector Prime Power Tank Injector Transmission Line Induction Cells Trigger Units Blumlein Charge Units Blumlein Cable Headers	Oil	3000 2000 10 x 64=640 150 x 32=4800 150 x 32=4800 4 x 32=128	15,000 gallons
PPT Liquid Resistors Radial Resistor	Water/Sodium Thiosulfate	15	15 gallons
Injector Blumlein Peaker	Glycol/Water	30	30 gallons
Injector Blumlein & Transmission Lines	Glycol	2000	2000 gallons
ICPPS Blumlein	DI Water ≥ 16 MΩ	32 x 70 gallons	2240 gallons + Supply
Final Focus Magnet Cooling	Glycol	20	20 gallons
Magnet [compressor – DII only] cooling	Water		150 gpm

DARHT Axis 1 Gases

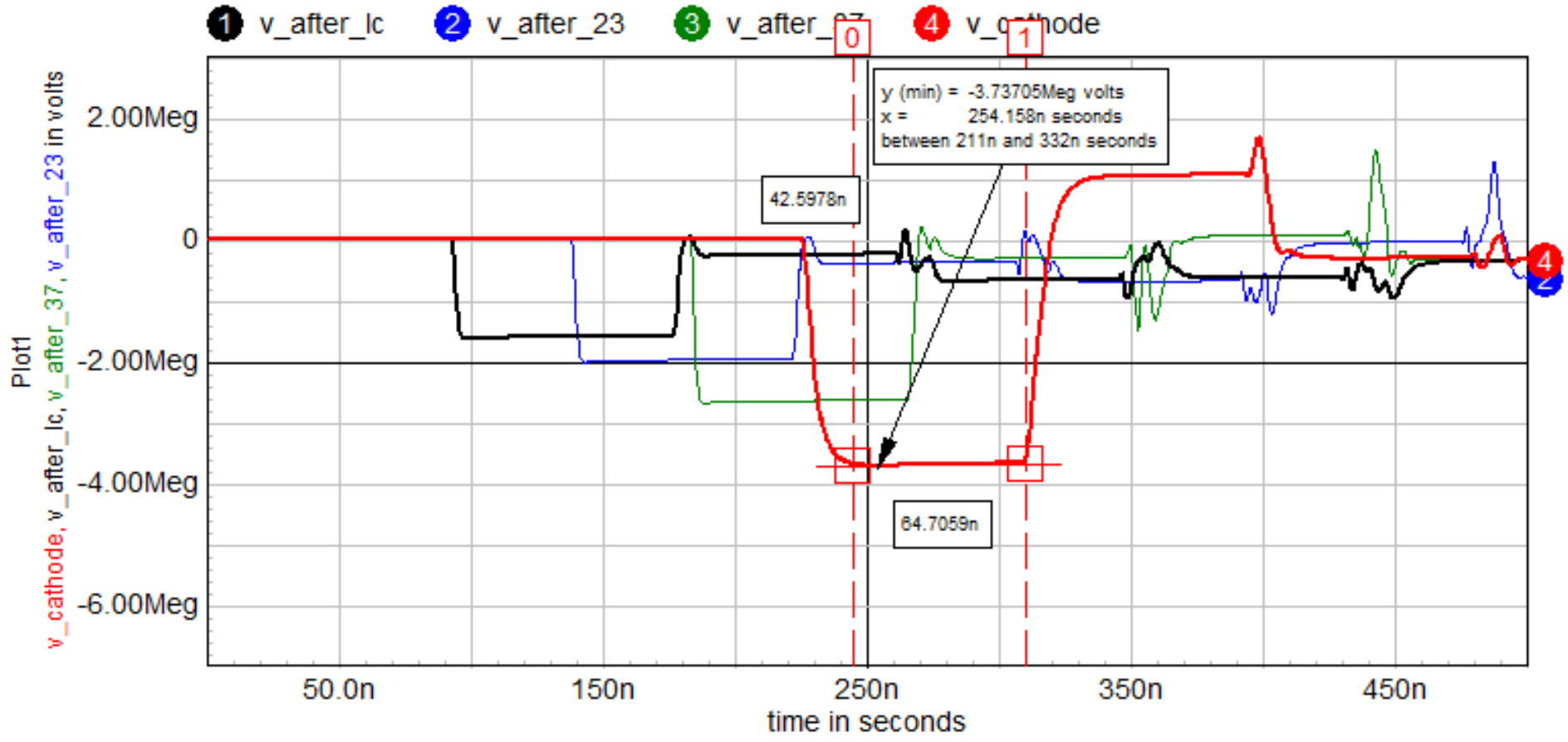
Region	Fluid	Each	Total
Injector PPT Switch	Dry Air		60 psig @ 15 SCFM
Injector Blumlein Switches ICPPS Blumlein Switches	SF6	120 psig @ 15 SCFM 32 x 60 psig @ .2SCFM	120psig @ 22 SCFM
Injector Laser	Nitrogen		
Vacuum pneumatic Valves	House Air	120 psig	120 psig

DARHT Axis 1 Hardware Summary

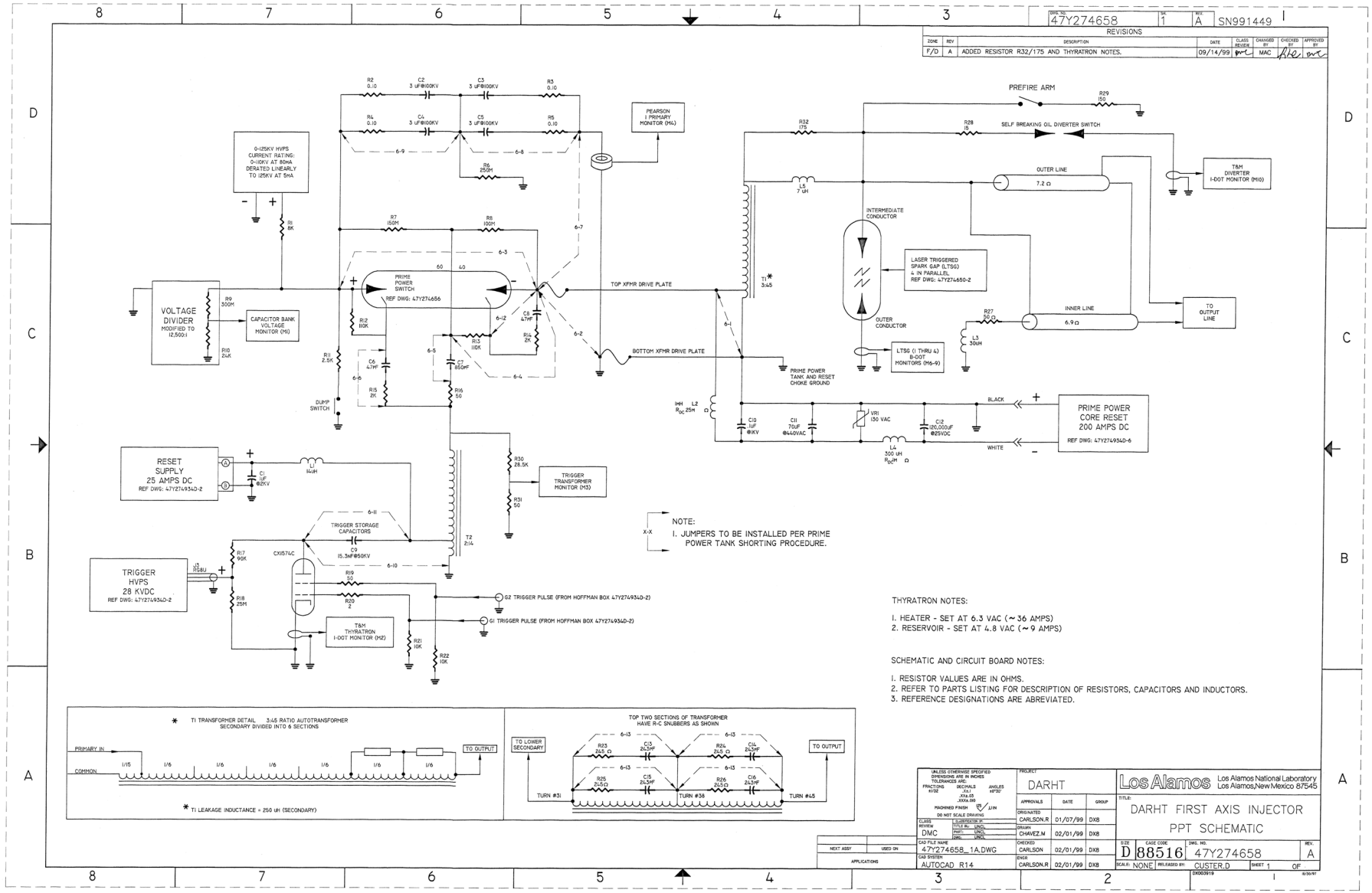
- **Perfomance**
  - High quality results
- **Reliable**
  - Maintenance down time is always necessary but shouldn't become too obstructive to hydrodynamic experimental program
  - Large ticket maintenance items occur rarely (e.g. radial insulator, …)
- **Repeatable**
  - repeat days/months later with same result
    - Critical feature for hydrodynamic experiments
      - Accelerator/Radiography is diagnostic – Hydro is experiment

DARHT Axis 1 Injector Model Voltage Waveforms

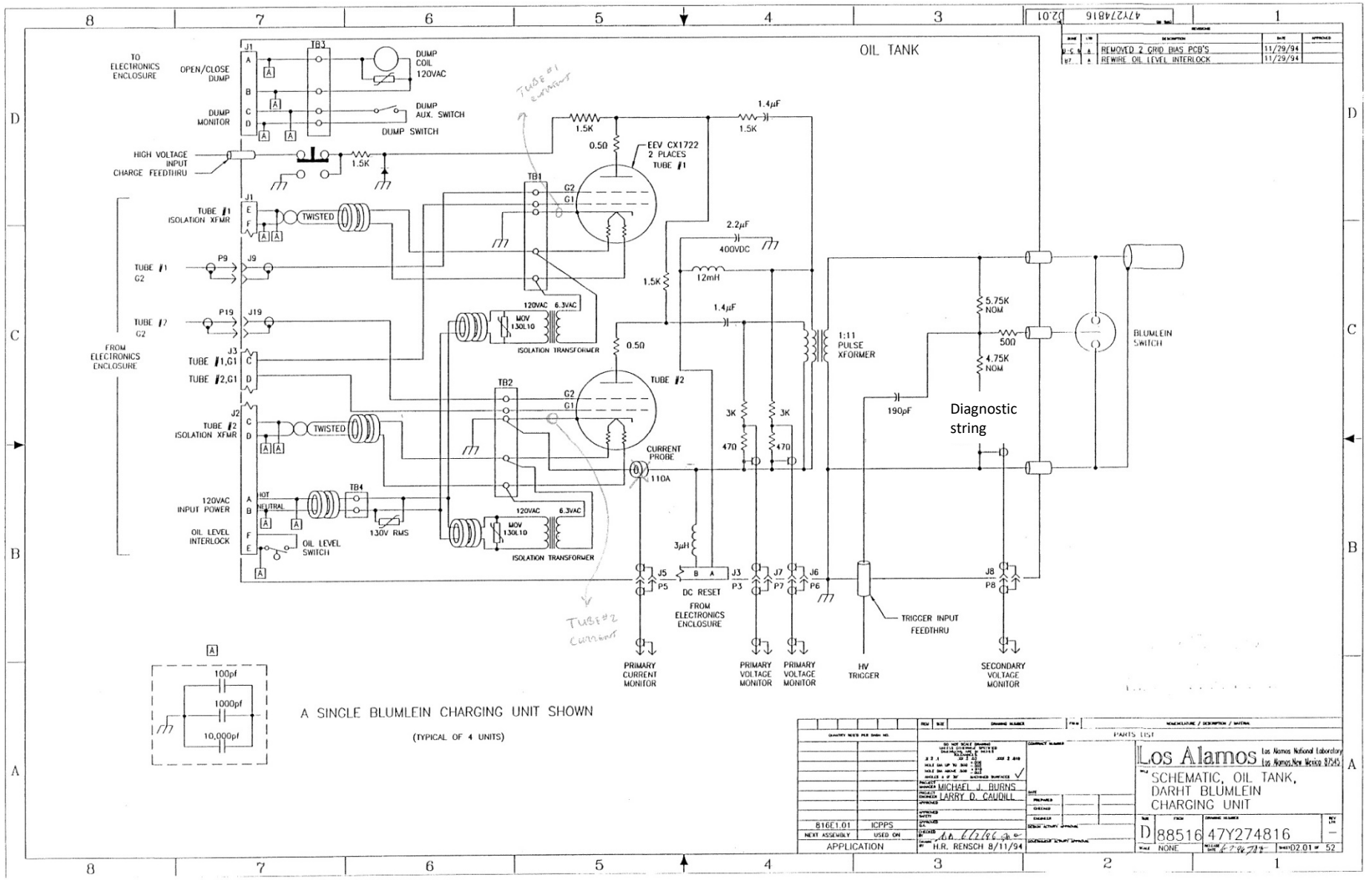
Analysis by Chris Rose



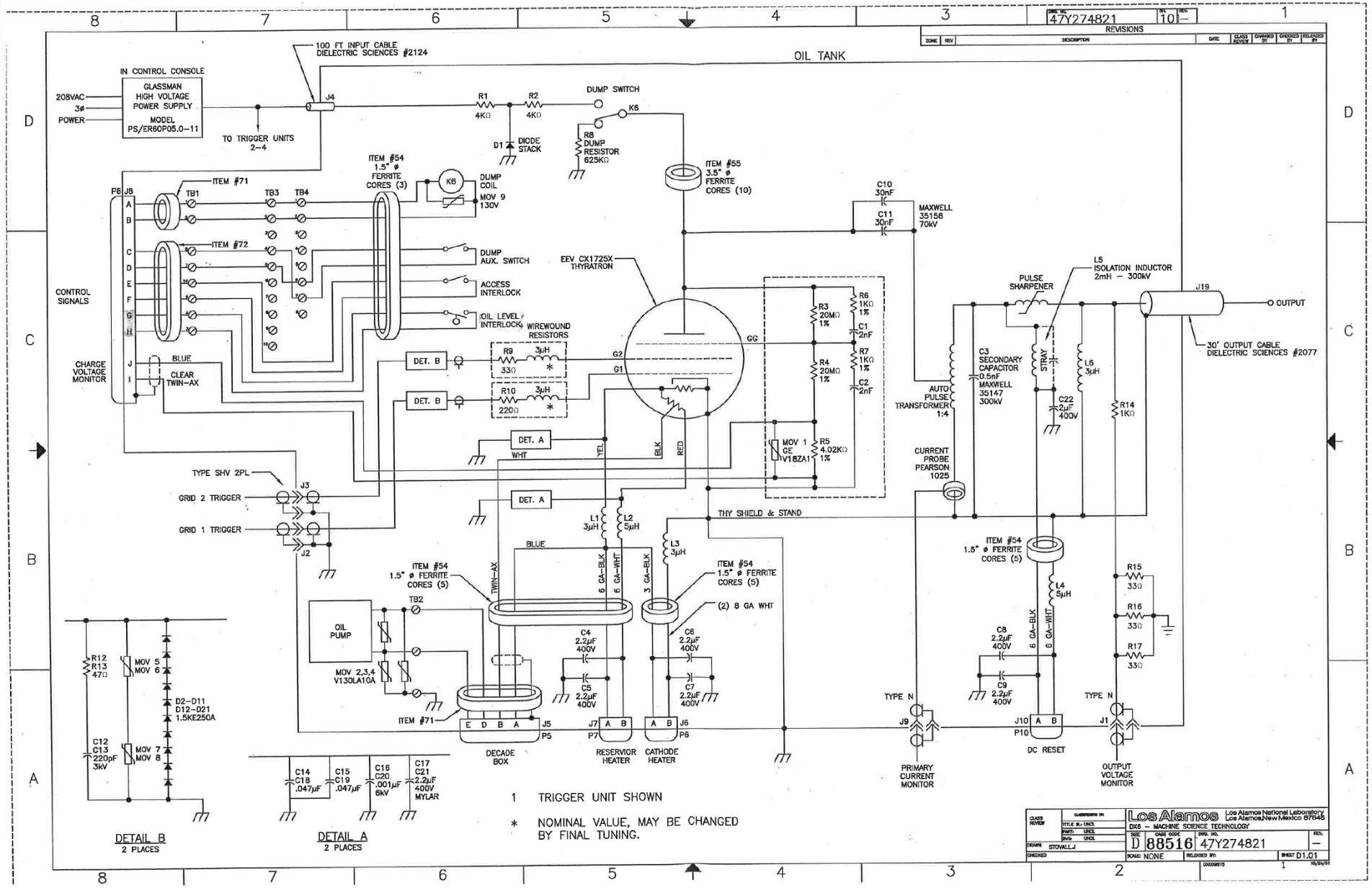
PRIME POWER TANK (PPT) Circuit Diagram



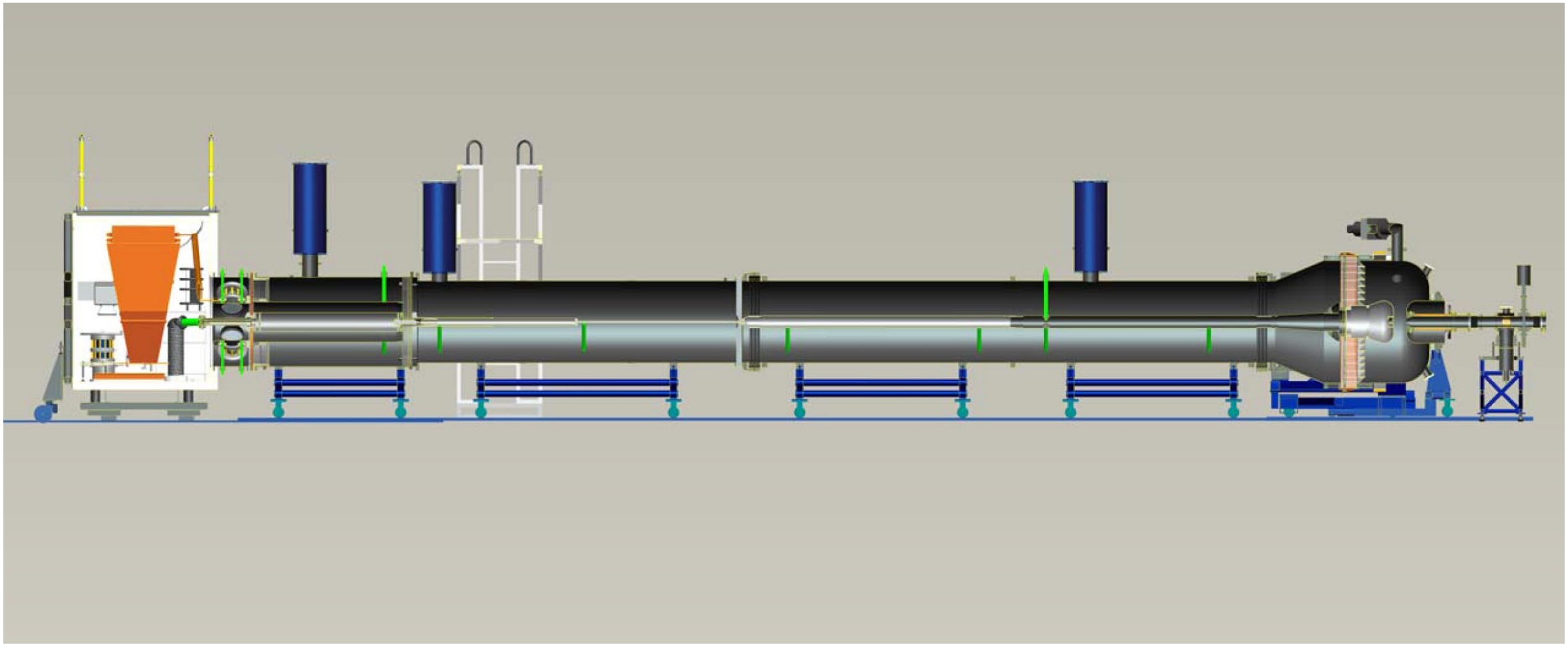
Blumlein Charge Unit (BCU) Circuit Diagram

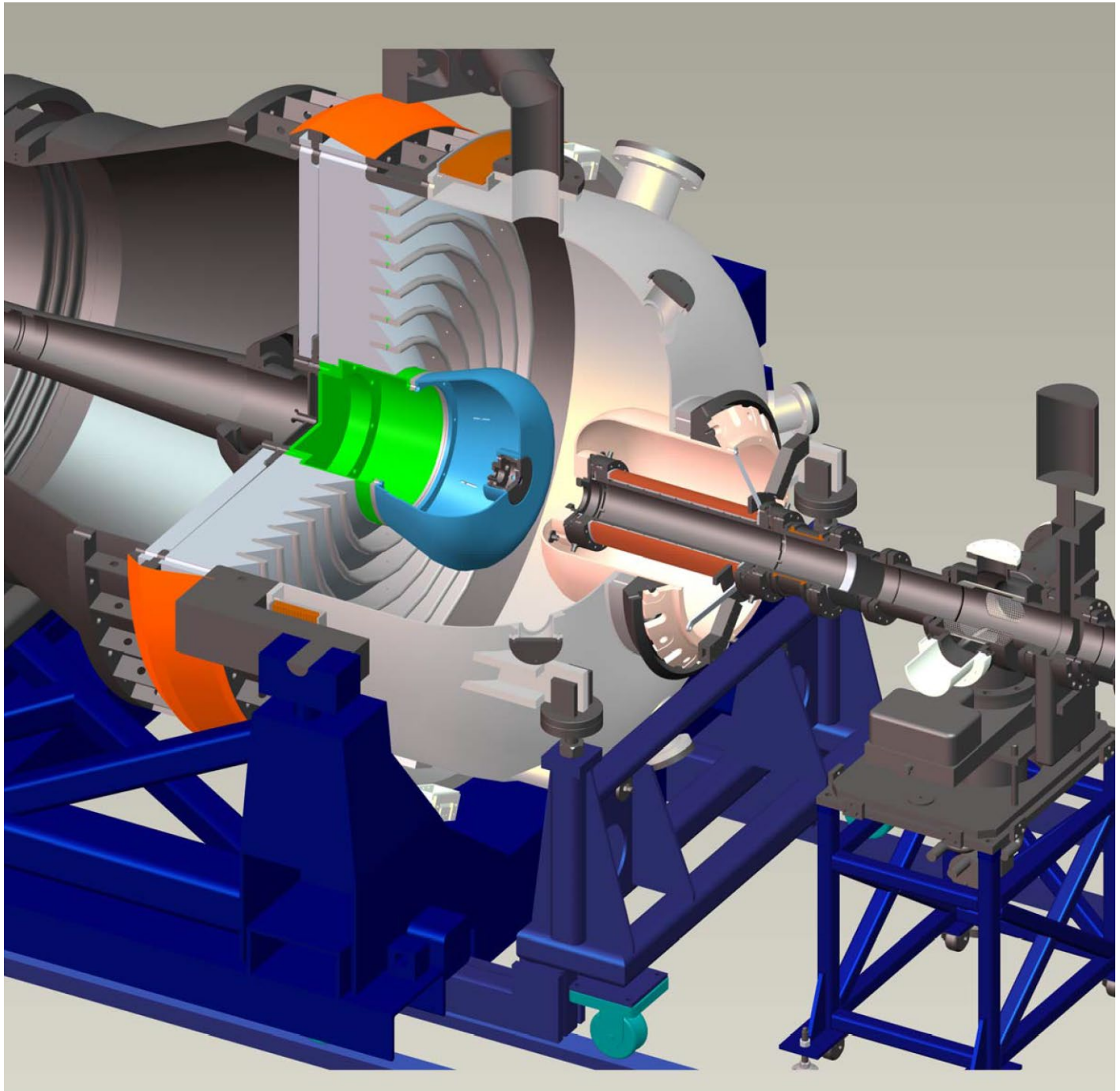


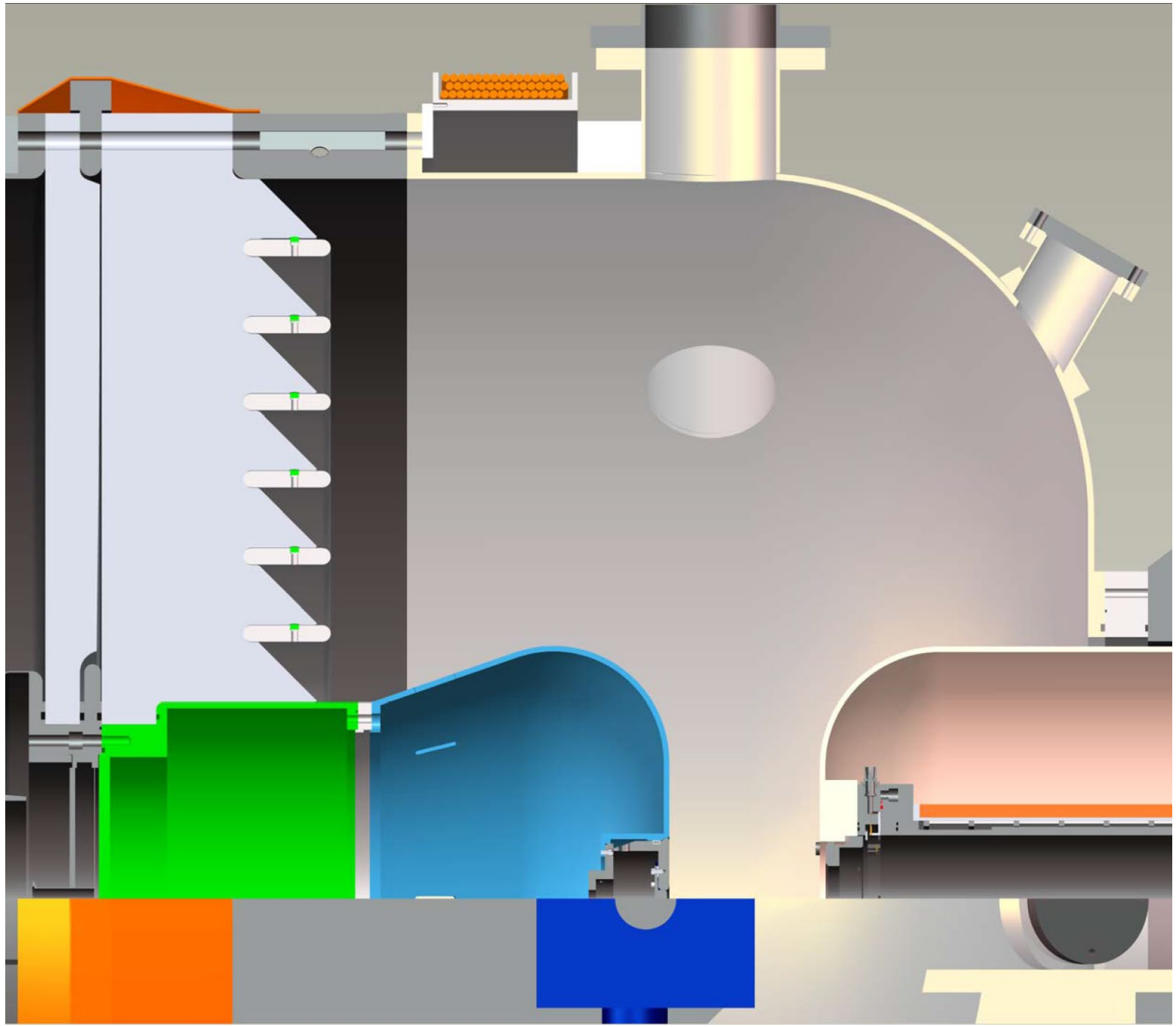
Trigger Unit (TU) Circuit Diagram

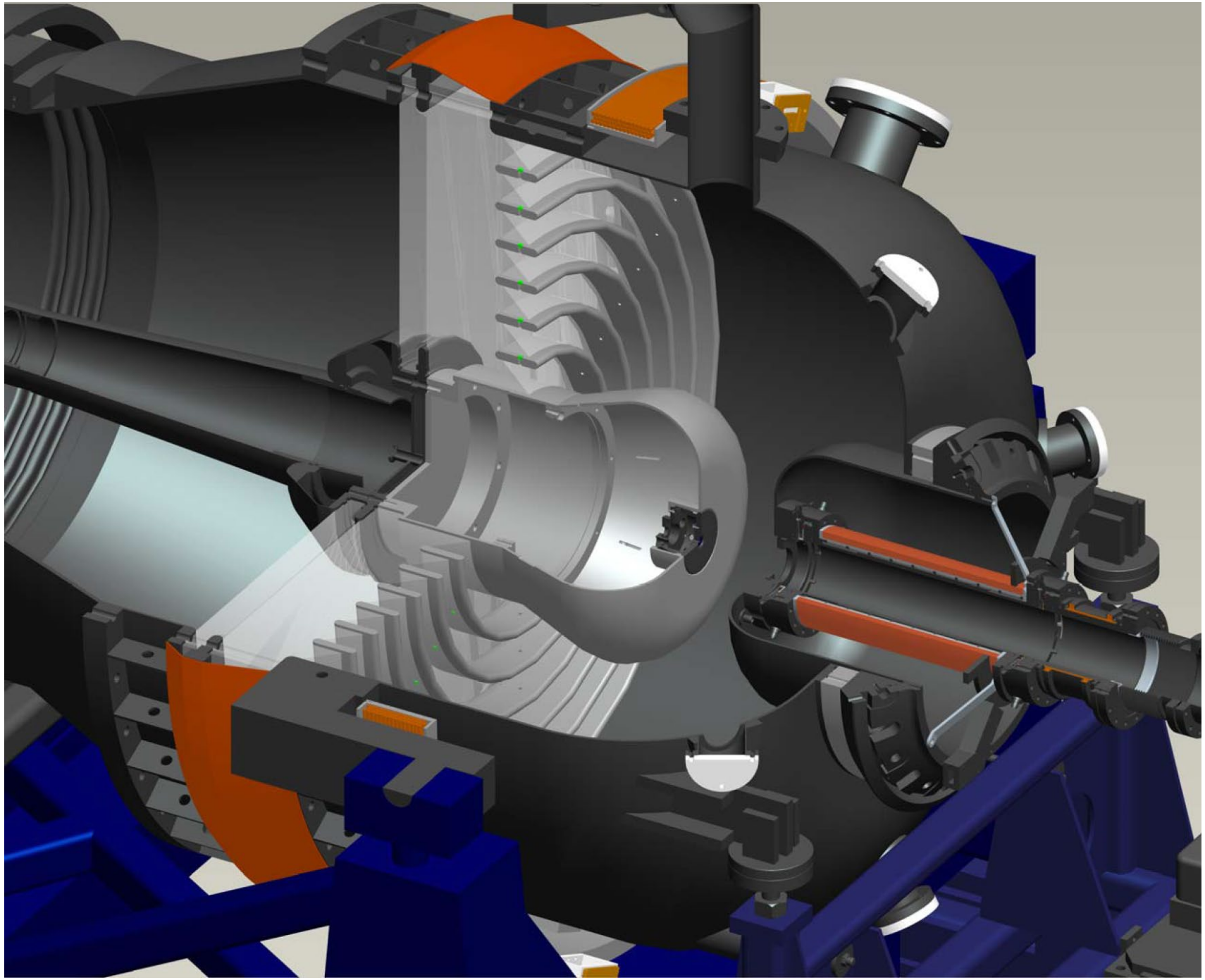


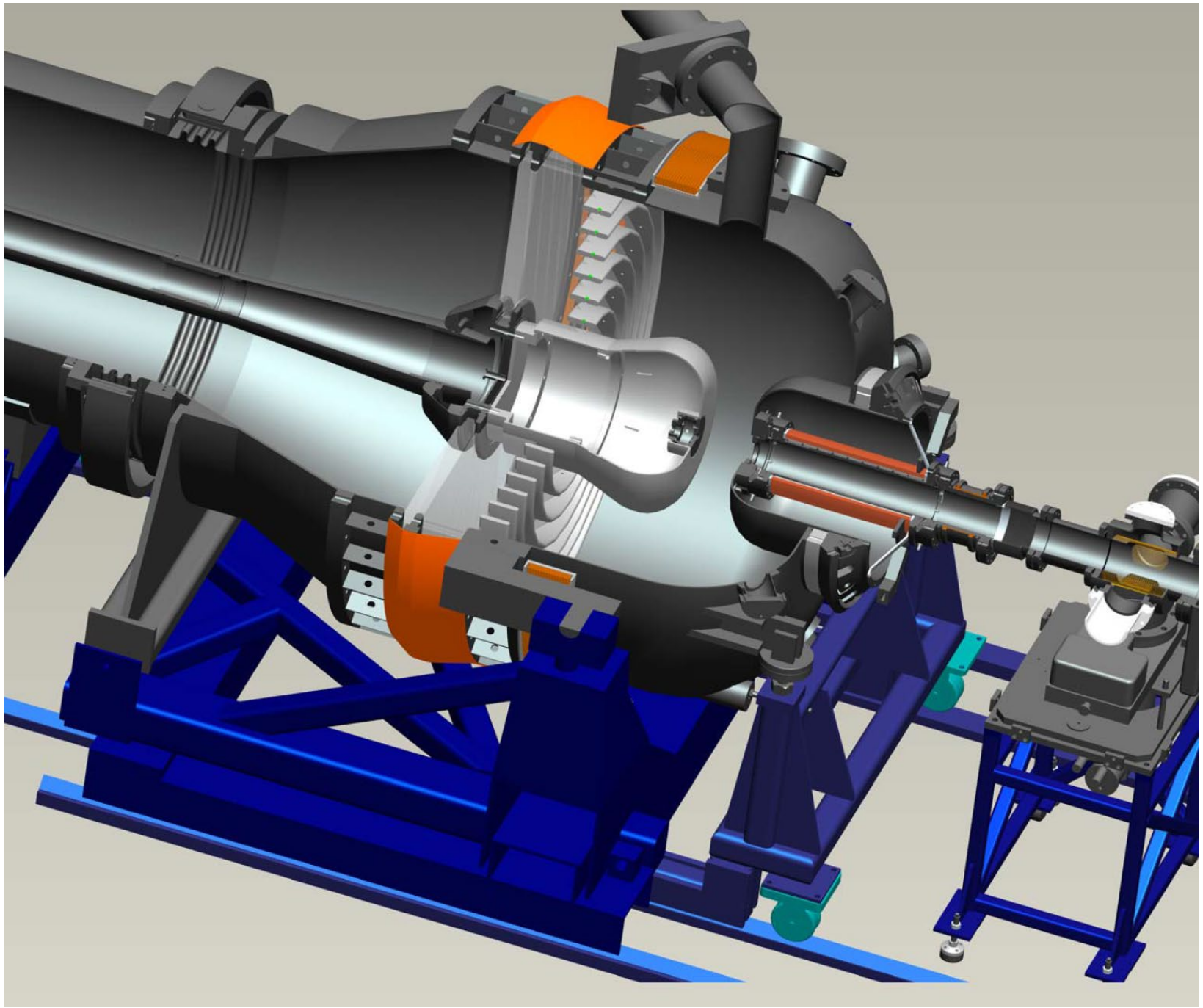
Additional DARHT Axis 1 Graphics











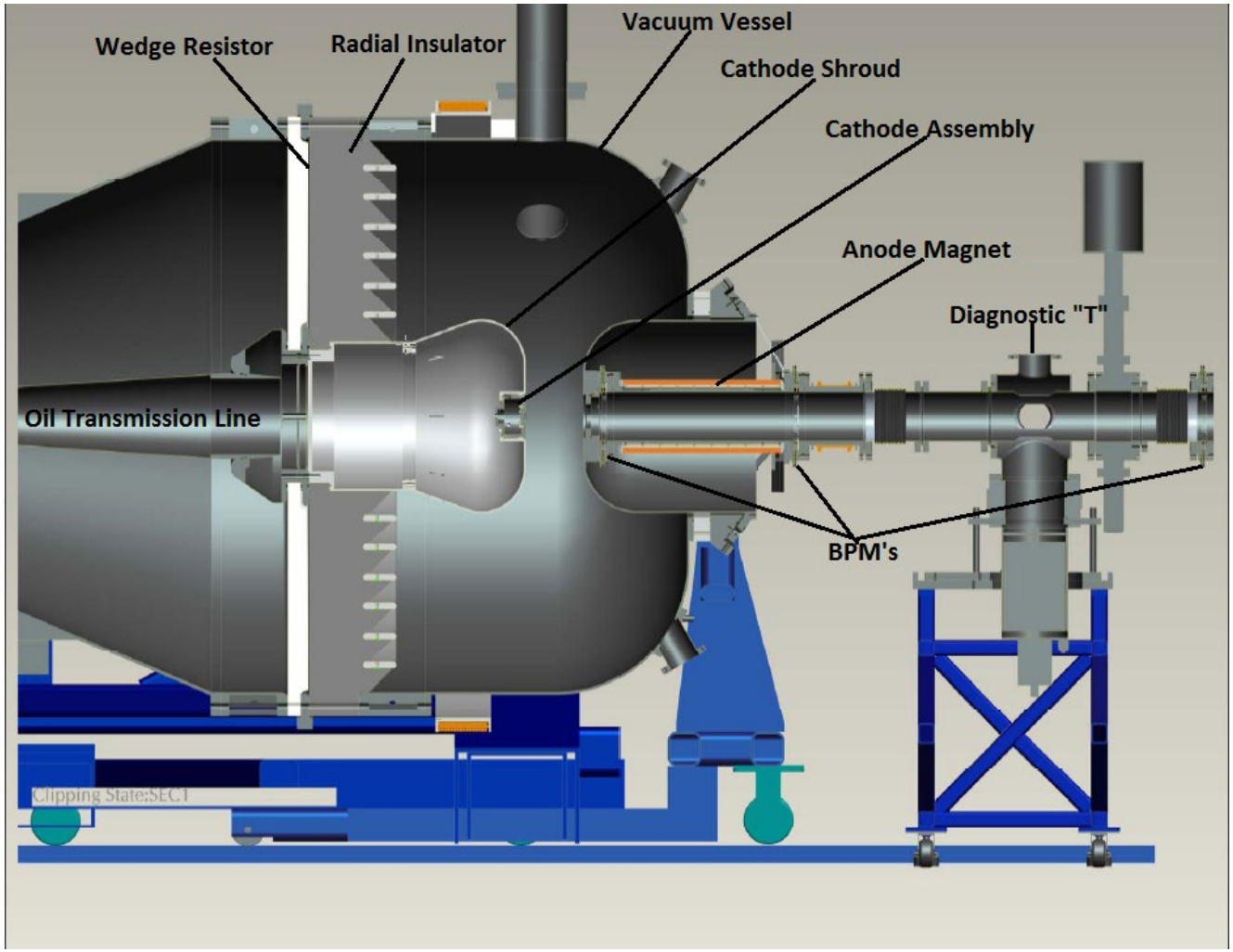
DARHT Axis 1 System Overview Part 2 (Beam Dynamics)

David C Moir

Outline

- Injector Cathode
- Injector Performance and Beam Transport
- Induction Cell Acceleration and Transport
- Spinning wheel
- Transport Measurements
- Beam Stop
- Final Focus and Target box
- Radiation Generation
- Explosive Experiment Execution
- Operations Documentation
- Conclusion

Injector Configuration



25mm Cathode in Anodized Aluminum Holder

Velvet cathode material

Rayon (with or without silk) works best.

Velveteen (cotton) spot size at target not reproducible.

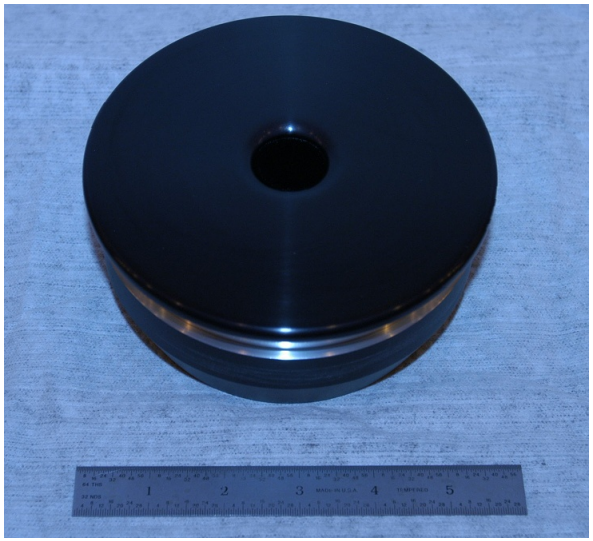
Velvet (Acetate) almost no emission.

50mm cathode velvet lasted 7 years ~2k shots before noticeable degradation of beam (current and spot size).

Cathode can be changed in 4 hours with overnight pumping ready the next day

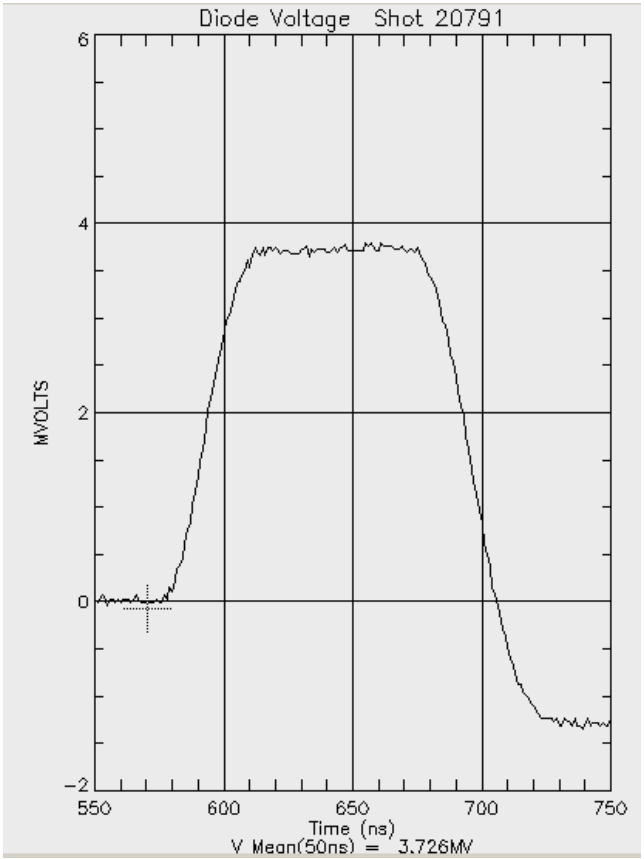
Quiver of cathodes 19mm, 25mm, 50mm, 70mm

Velvet is recessed 3mm from the surface of the holder, critical for beam quality (minimizes edge emission)

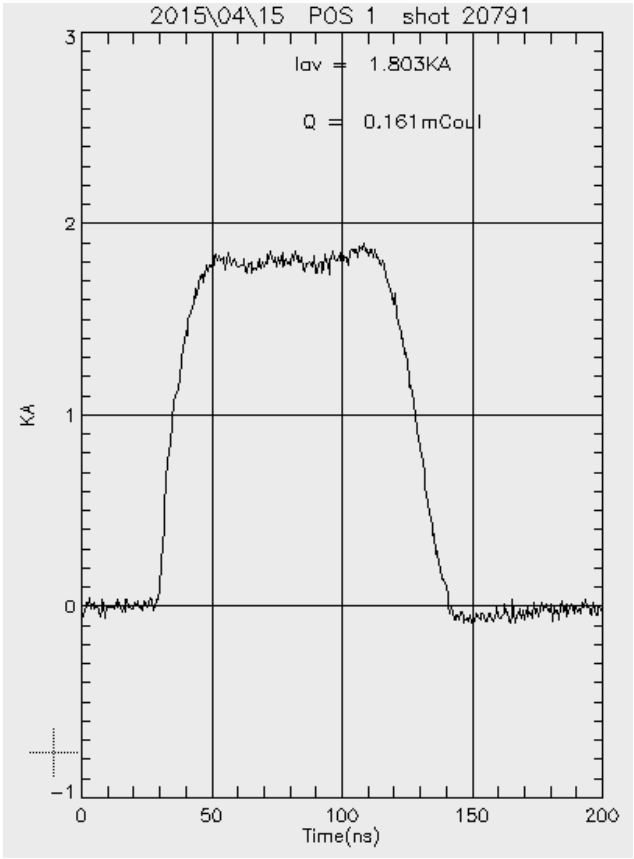


Injector Voltage and BPM1 Current 50mm cathode

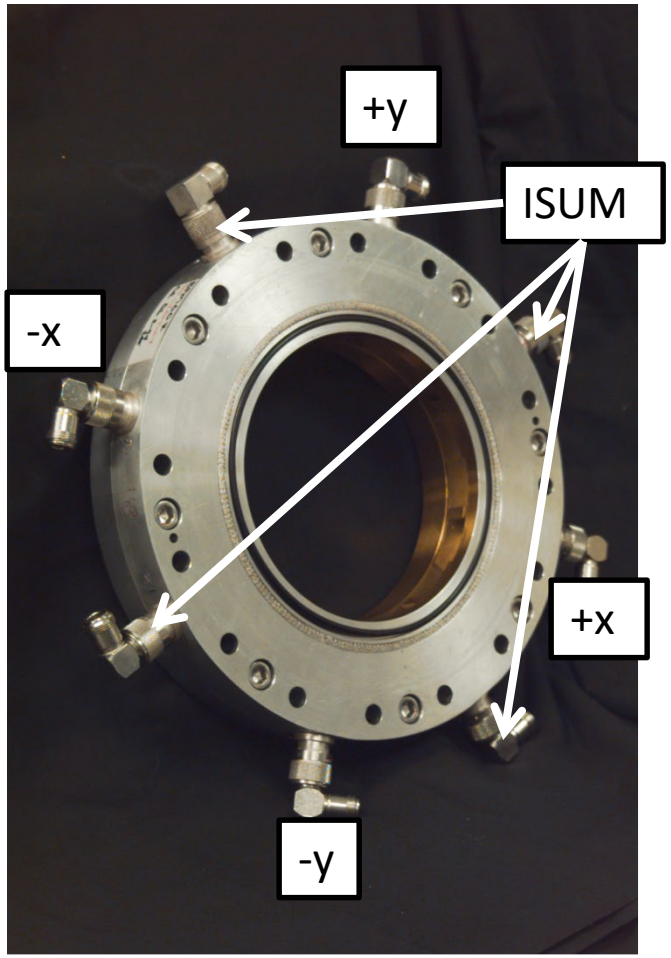
3.73 MeV



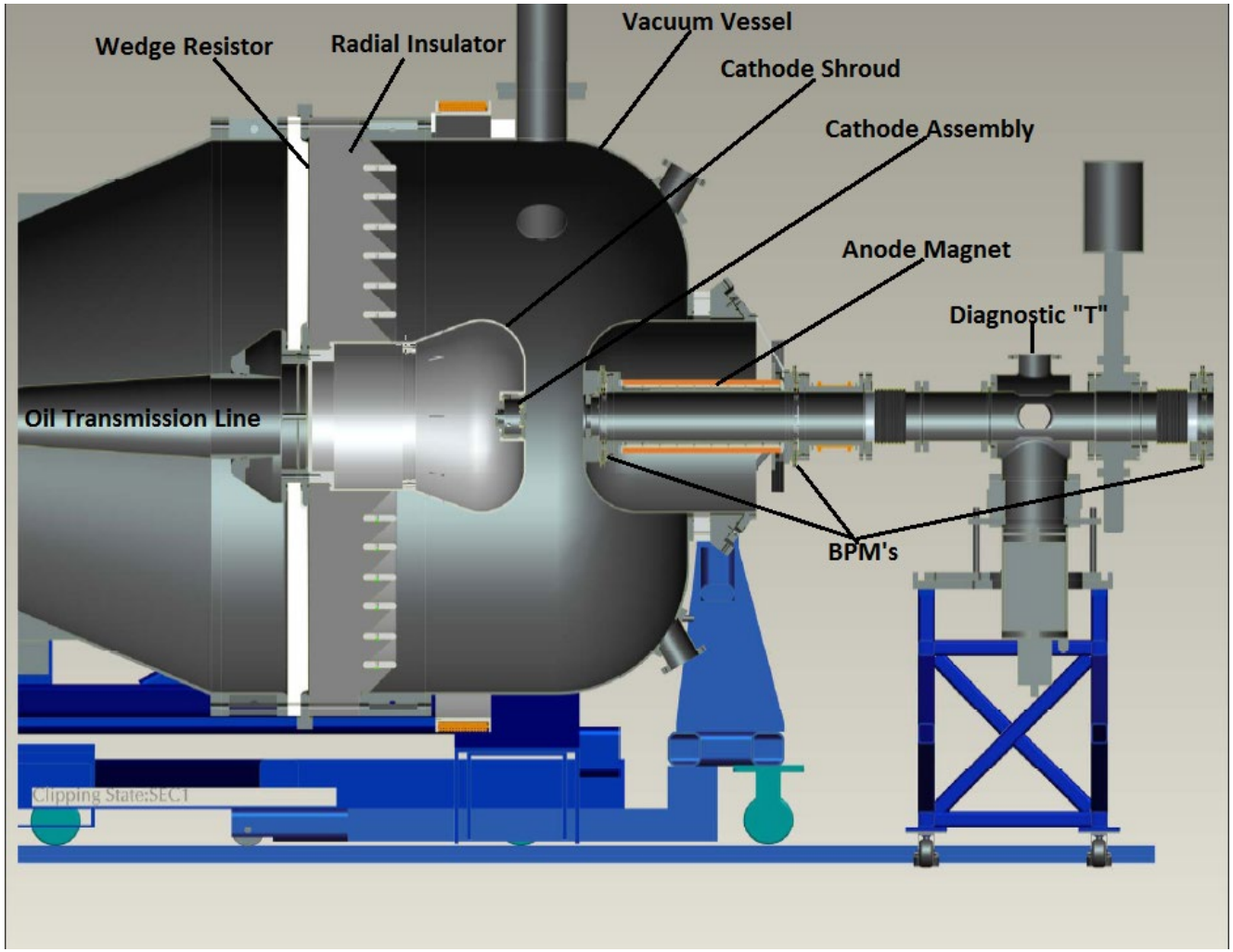
1.80 kA



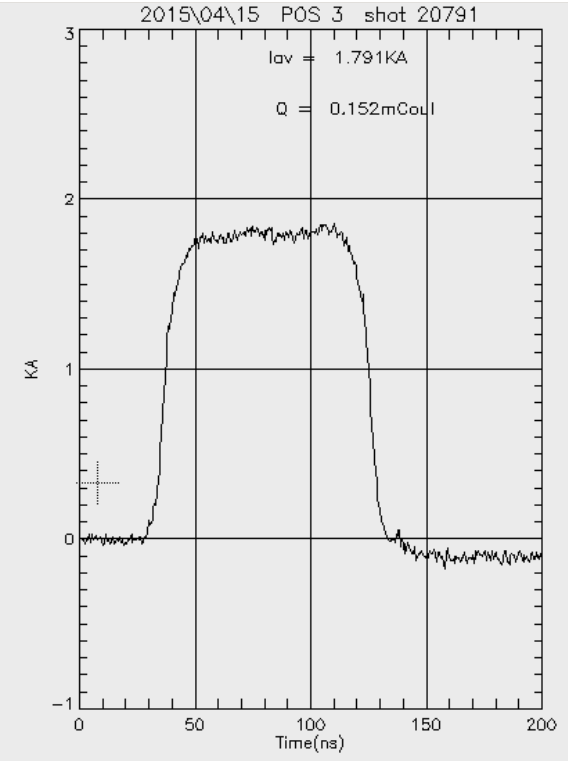
Axis 1 Beam Position Monitor (BPM)

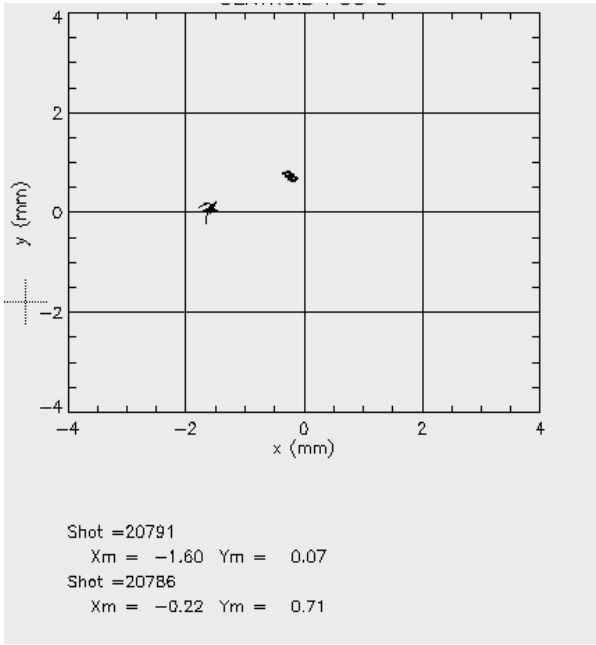


Injector Configuration



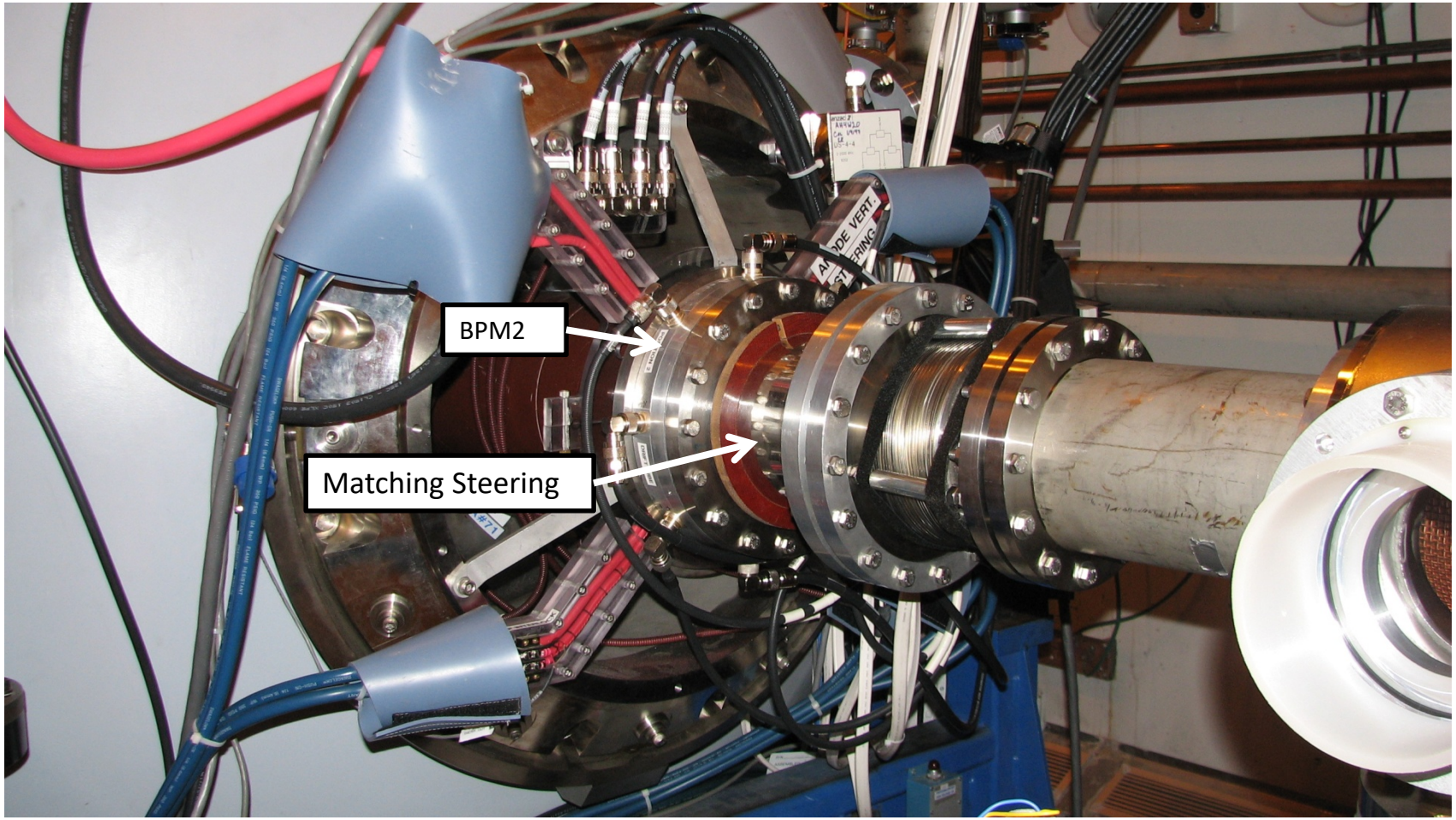
Welded SS Vacuum Dome Effect



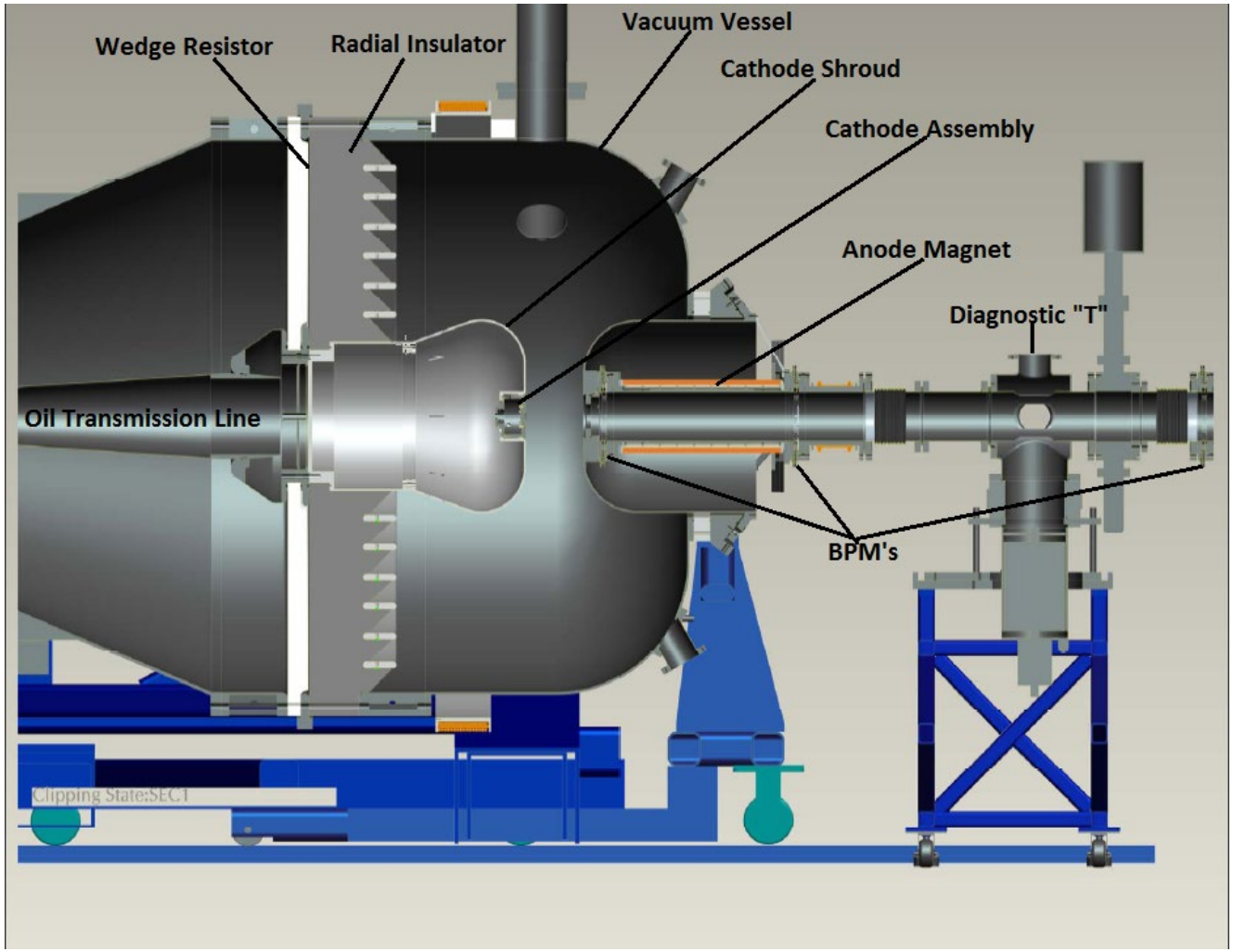


Anode magnet must be cycled a minimum of twice for reproducibility

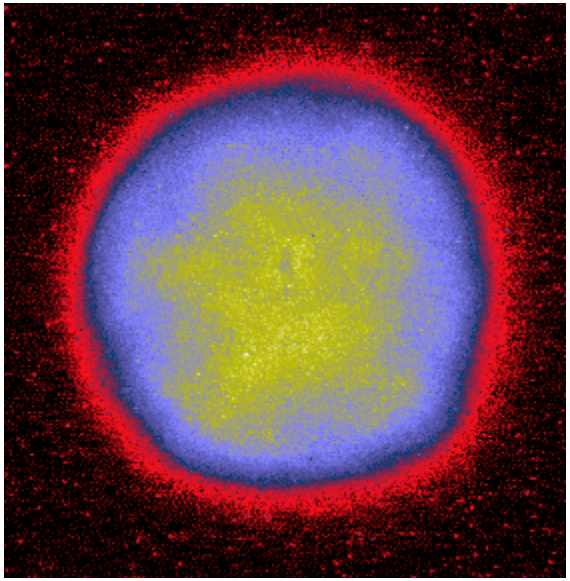
Anode Magnet

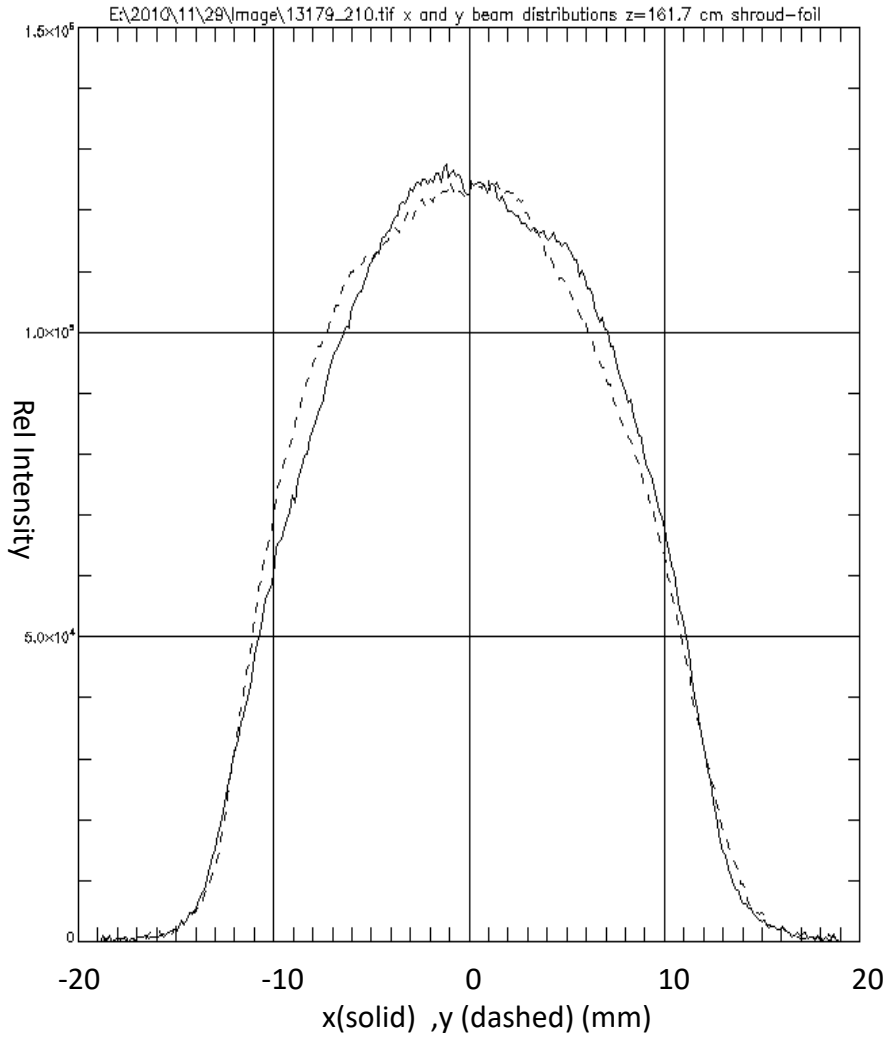


Injector Configuration

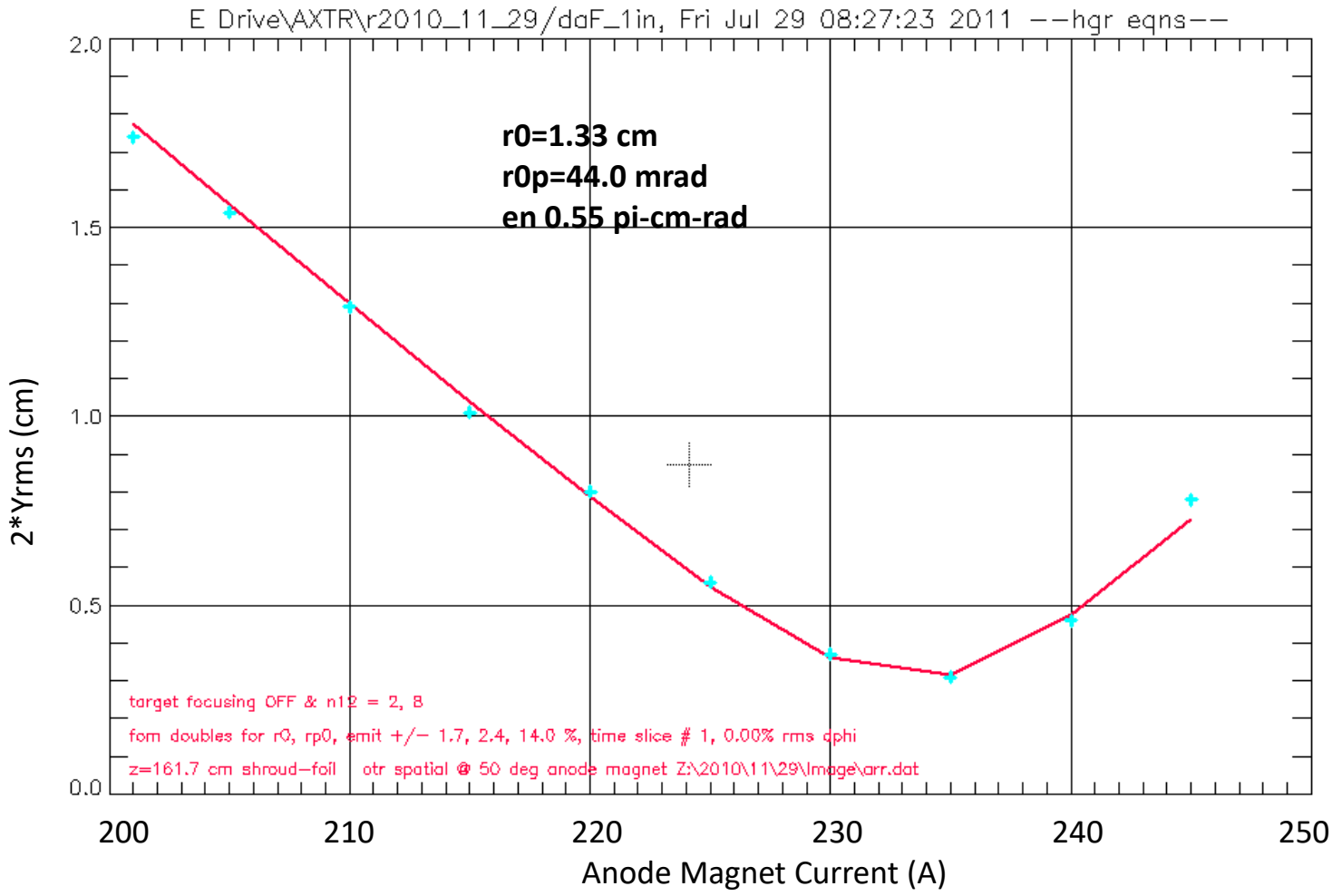


OTR Spatial Distribution with Anode Magnet Current @ 210A, Z=161.7cm from the 25-mm Cathode

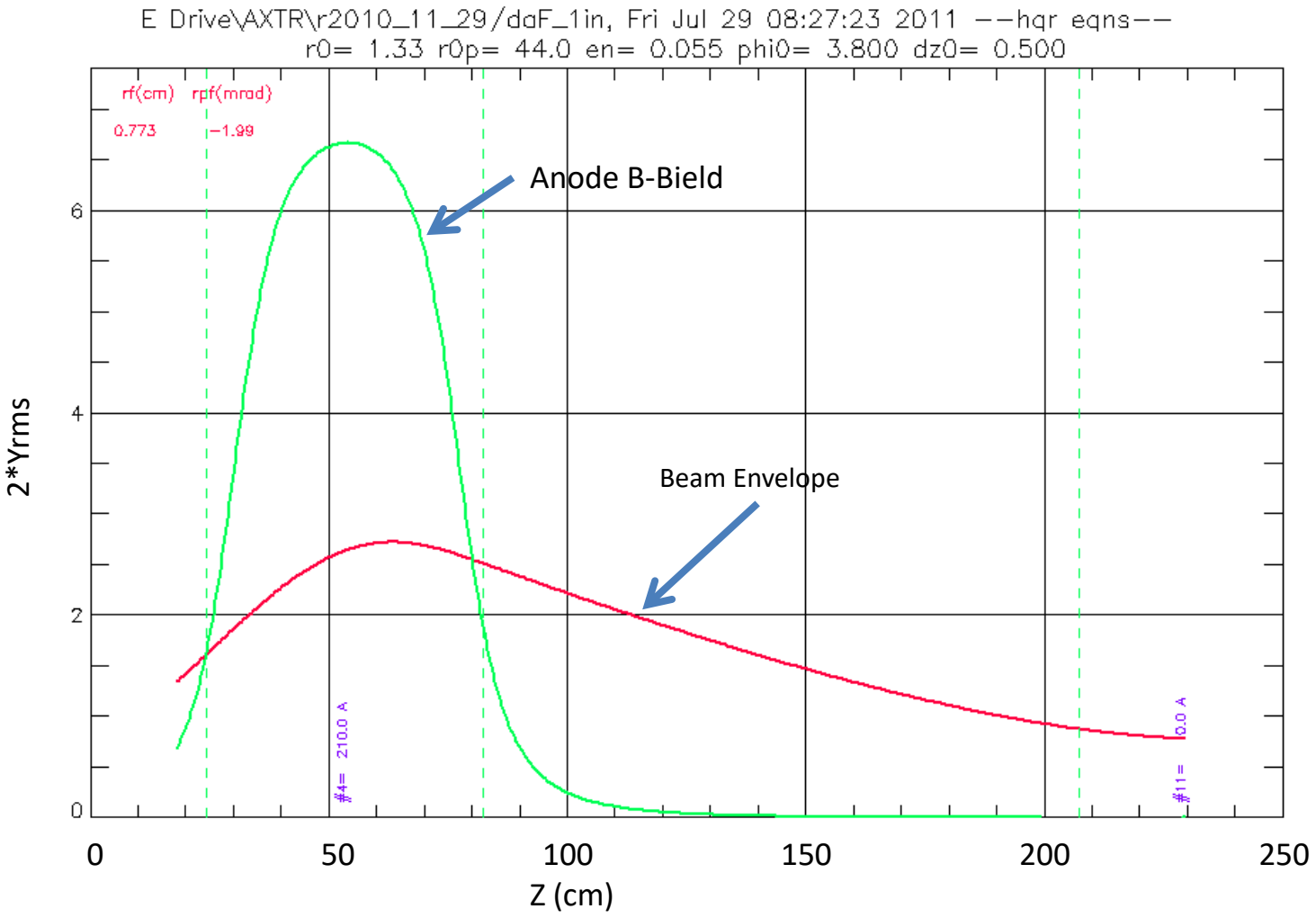




XTR fit to 25mm Cathode Injector Data

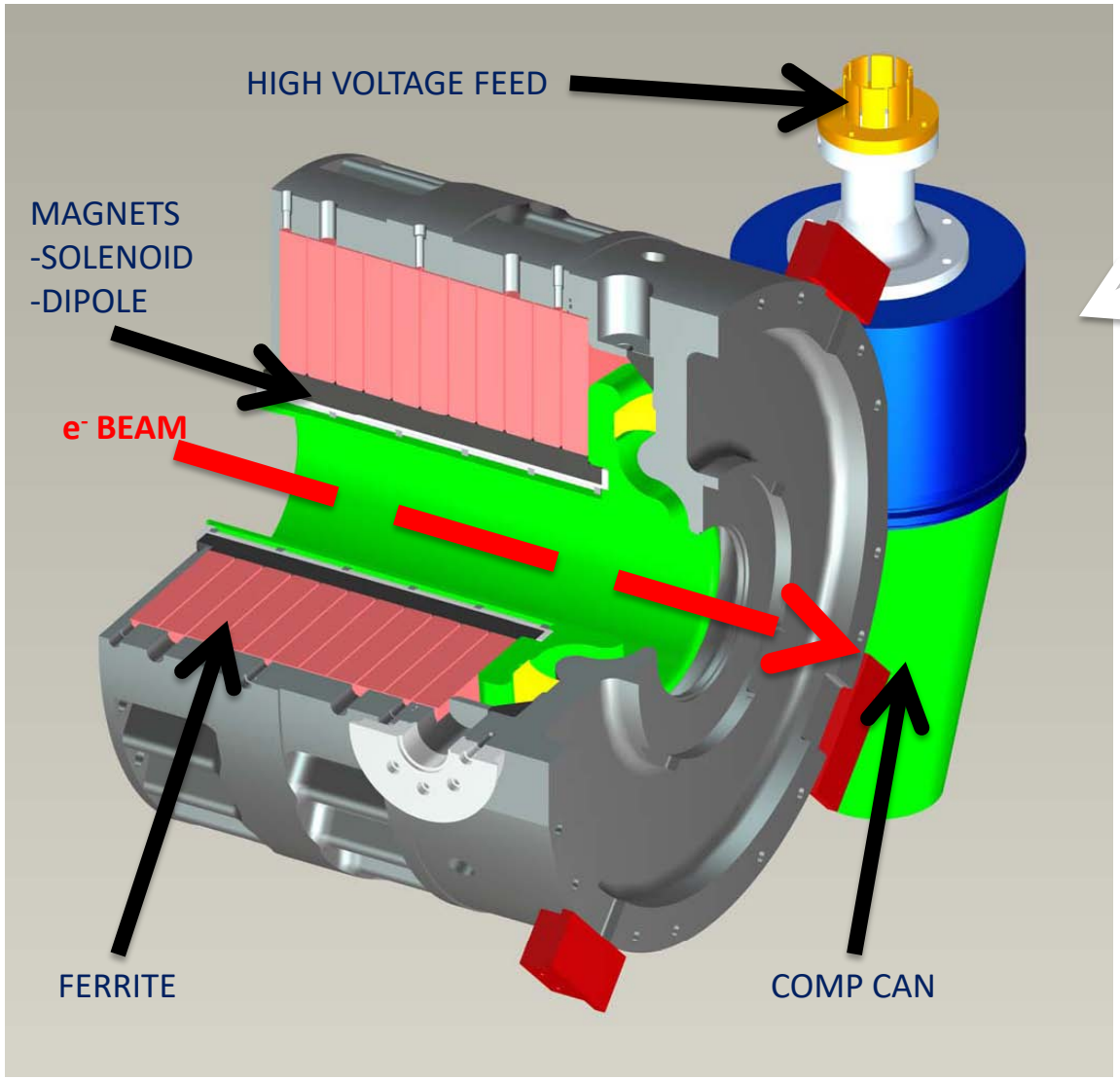


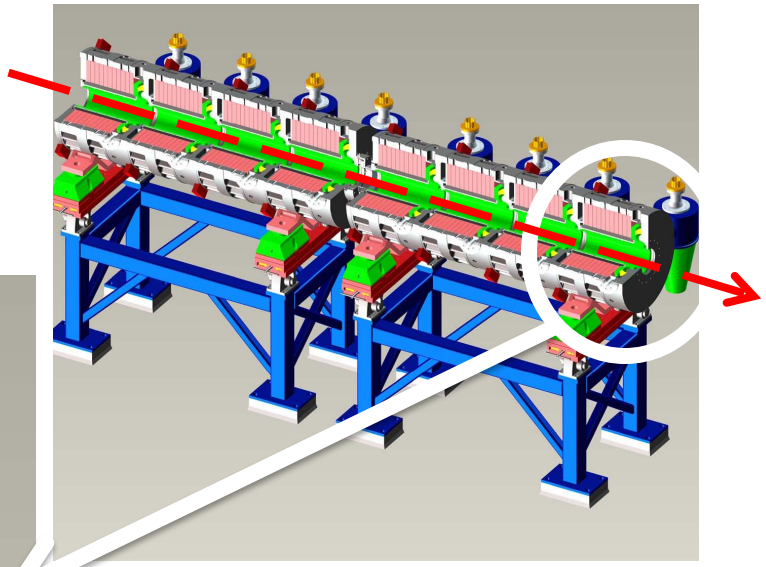
XTR Transport using Initial Conditions from Fit to Injector Data (25mm Cathode)



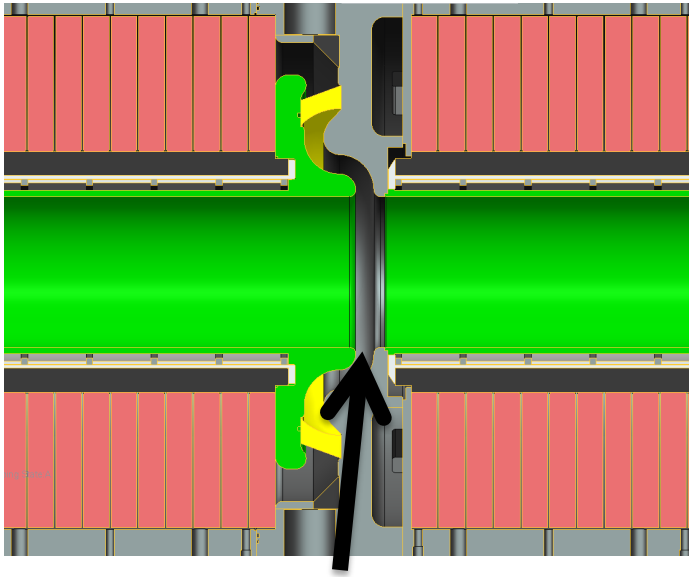
DARHT AXIS I

INDIVIDUAL CELL





CELL BLOCK ASSEMBLY



ACCELERATION GAP

Cell Magnets

- 2 kG peak field
- Square (0.25”) hollow conductor
- Quadrufilar (4 conductors per layer) wound 90 degrees apart to reduce transverse dipole fields
- Homogenizer rings reduce axial field tilt (x5.5) 6.35mm square located every 63.5mm
- Quadrufilar magnets with homogenizer rings reduced magnet tilts on the order of 0.5 mrad
- Dipole trim coils inside homogenizer rings with integrated dipole field of 0.58 kG-cm.

Cell alignment

- Outside cell diameter concentric with bore.
- Assembled on rails that are straight and parallel to 25um.
- Cell mechanical alignment within 250um cylinder.

Beam Break-Up(BBU) Instability and Transverse Impedances

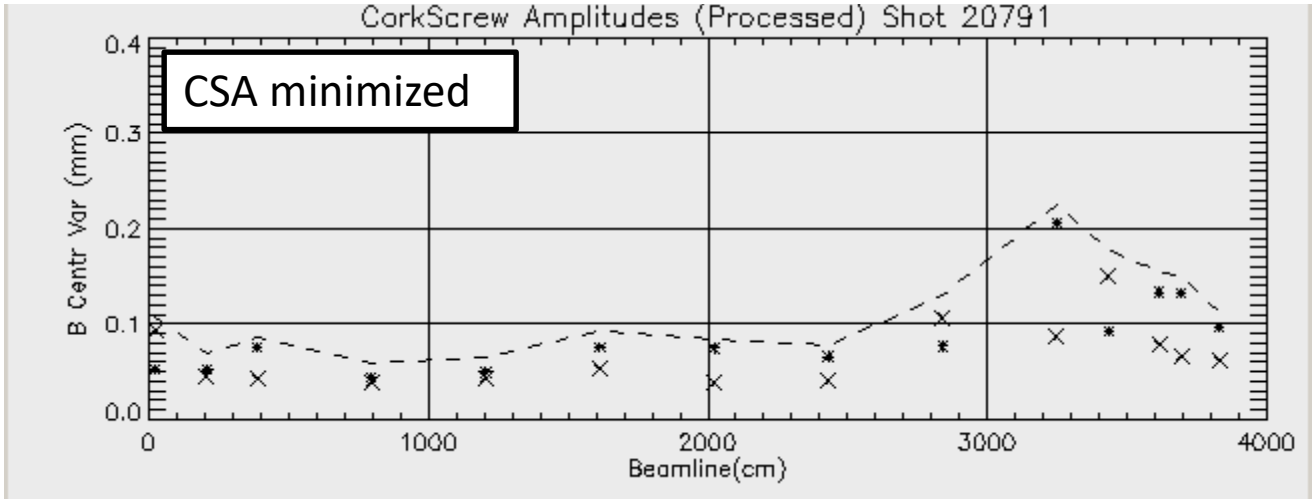
Each cell has an asymmetric rf response to a misaligned beam as it passes. The response is amplified by multiple cells.
Axis 1 cells were designed to minimize the rf response by minimizing the transverse impedance.
Below is a table showing properties of the principle BBU frequency for a single DARHT induction cell measured two different ways.

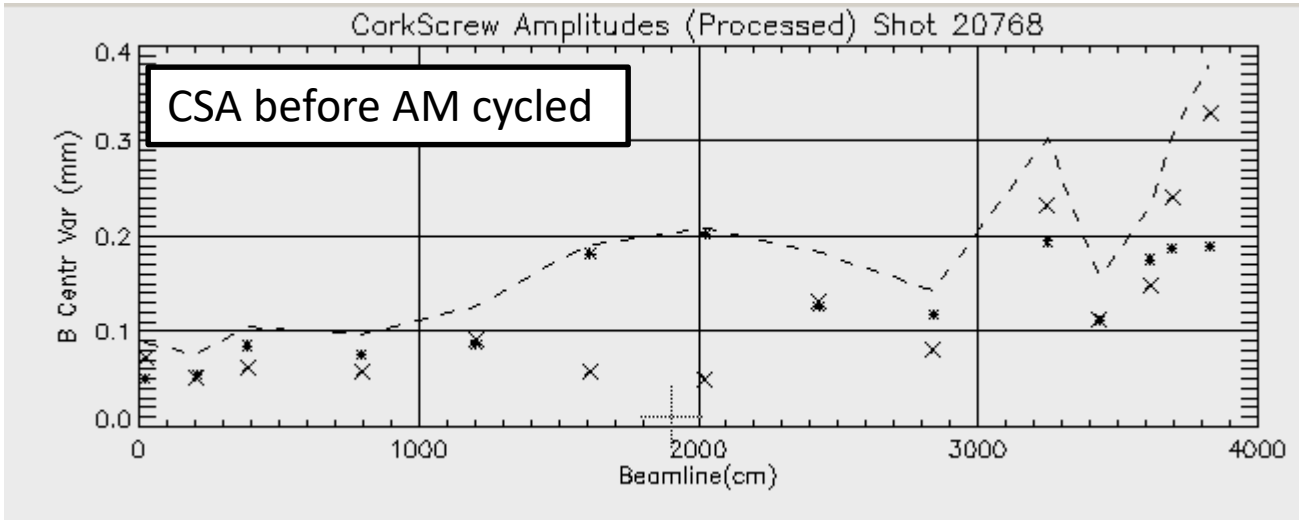
	Two wire TSD	LAMDA fit to BBU Gains
fx (MHz)	760	790
Qx	4.5	4.6
reZx(Ω/cm)	6.35	6.03
fy(MHz)	785	780
Qy	5.3	5.5
reZy(Ω/cm)	8.8	6.45

Corkscrew

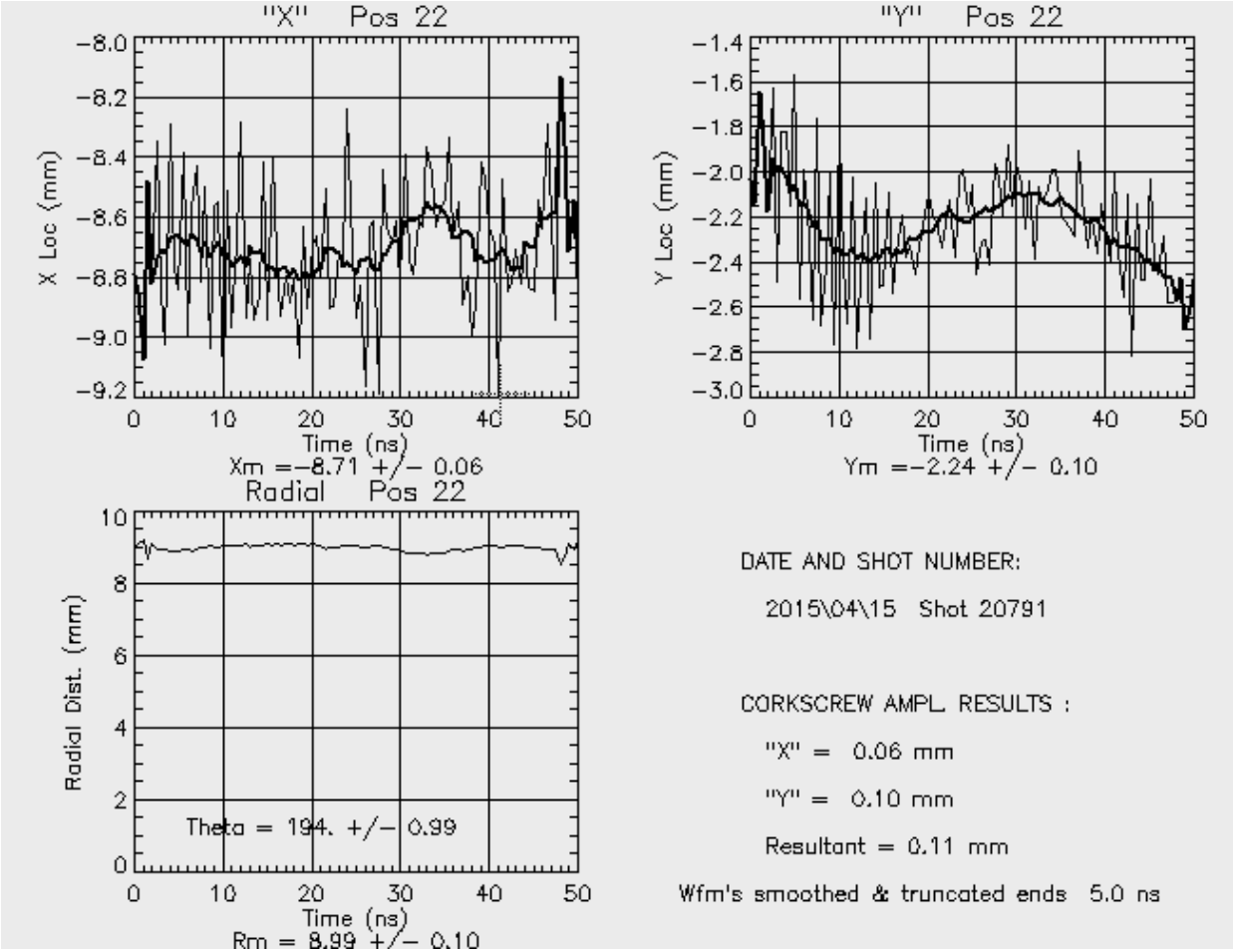
- Produced by electron beam energy spread and misalignment relative to magnetic field
- Energy spread of the injector initially dominates corkscrew
- Voltage flatness of the cells becomes important after the first two cell blocks

Corkscrew Amplitude through the Accelerator





Corkscrew/BBU Amplitudes at BPM22



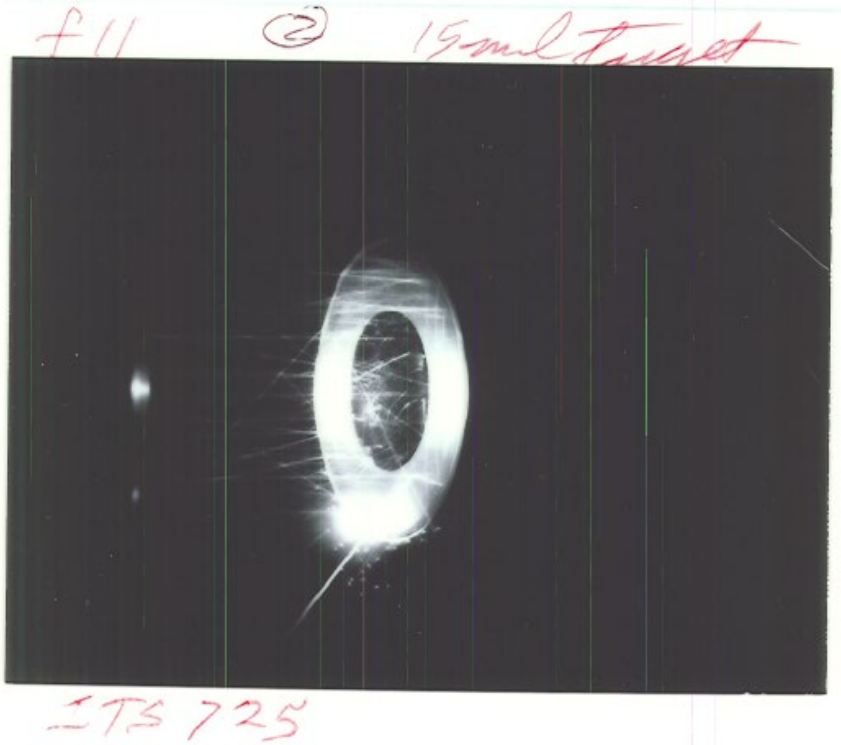
Downstream Steering

- Use cell 60 and 64 steering magnets.
- Center beam at BPM19 using cell 60 steering.
- Center beam at BPM25 using cell 64 steering.
- Each requires 4 machine pulses.
- Both are necessary when new cell solenoidal magnet tune is introduced.
- Usually cathode change only requires cell 64 steering.

Spinning Wheel

Necessity of Debris Blocker

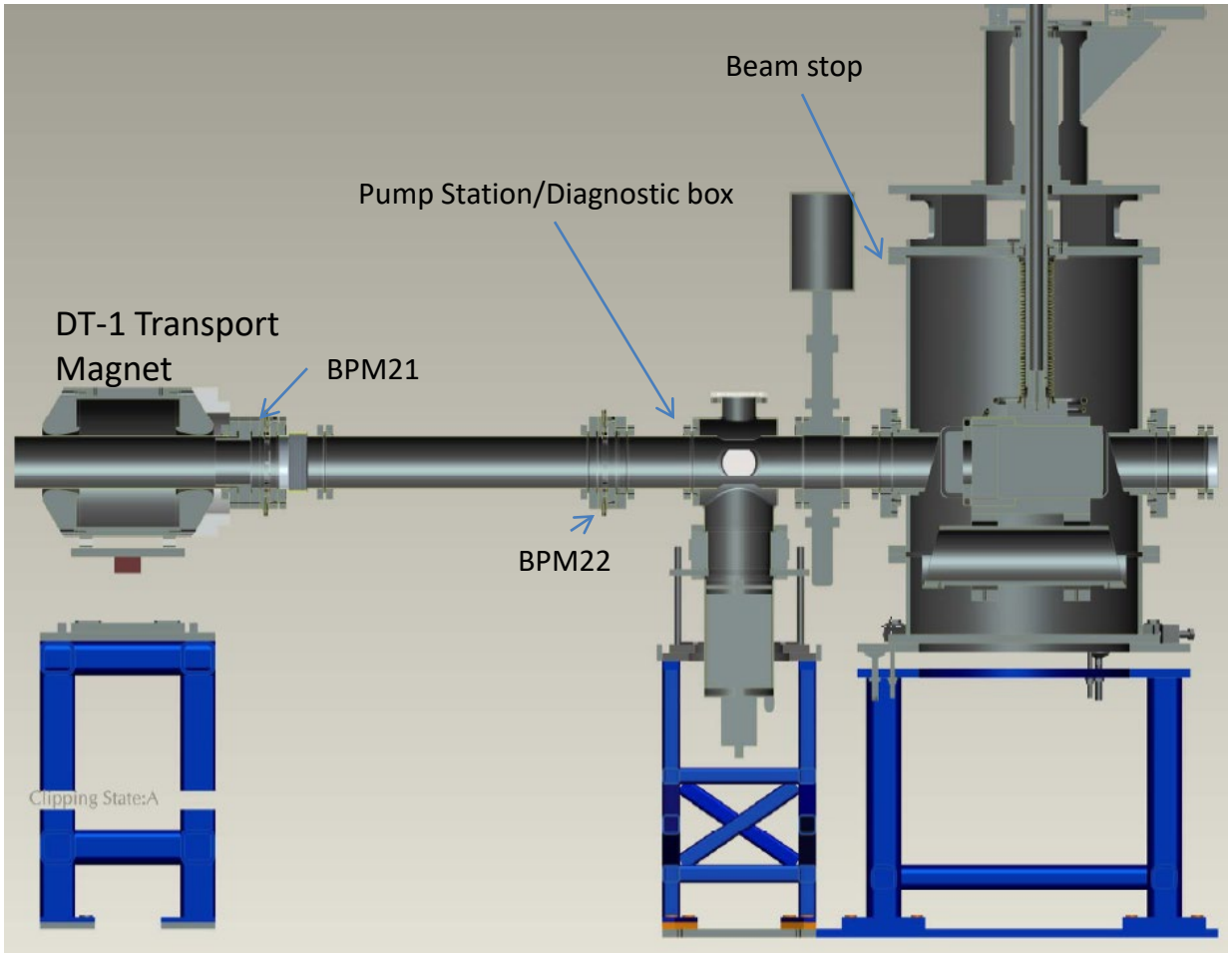
Open Shutter Photograph of ITS Velvet Cathode for Shot 725 (Milestone 3)



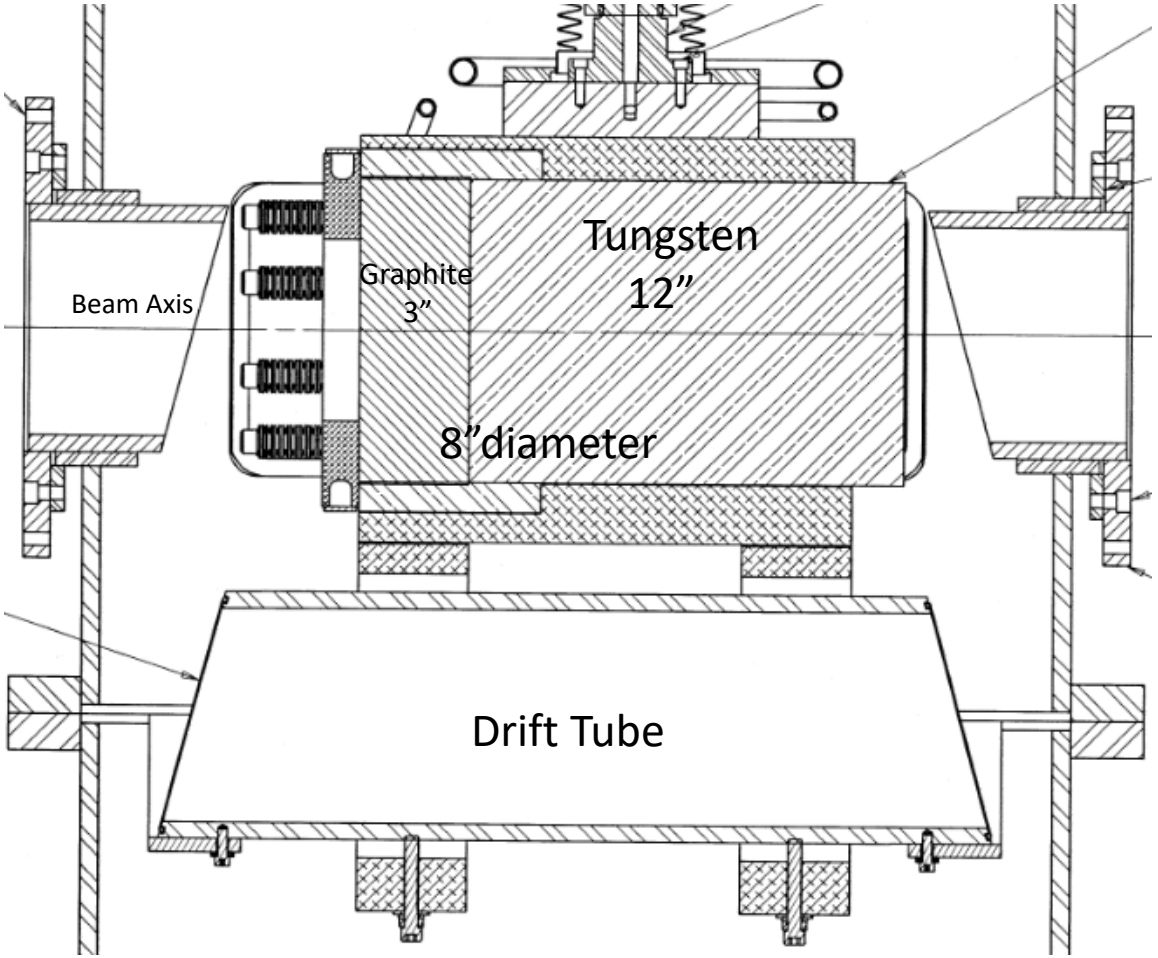
Debris Blocker or Spinning Wheel (Shutter)

- Debris produced by the focusing the e-beam on a tantalum target must be prevented from contaminating the HV surfaces of the accelerator and injector
- This is accomplished with two slotted wheels spinning in the same direction at different frequencies (50Hz and 40Hz).
- The shutter on the drift tube is open for ~0.75ms and closed for 120ms
- Tantalum debris has a max velocity of 7mm/μs.
- Fast valve was installed on Axis 1 with the spinning wheel. Transverse mode produced by asymmetric cavity of the valve increased target spot.

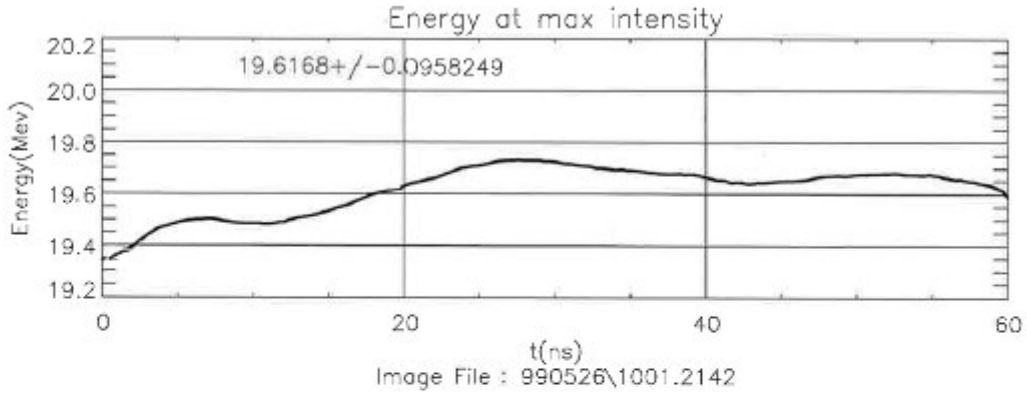
Downstream Configuration

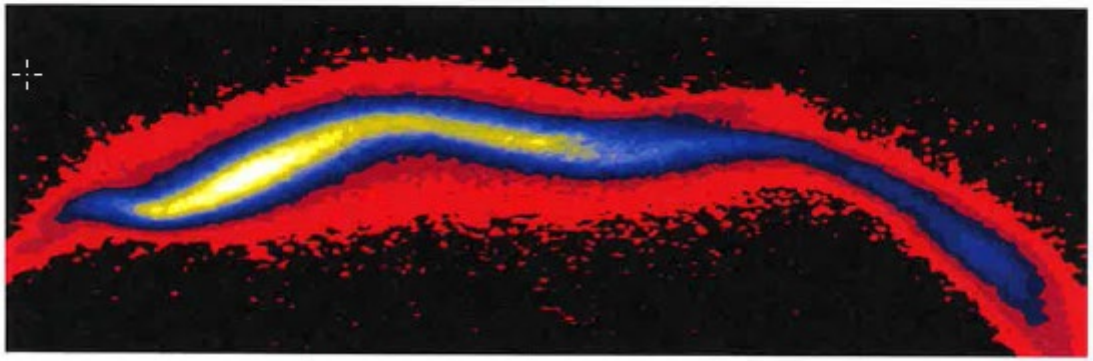


Beam Stop Configuration

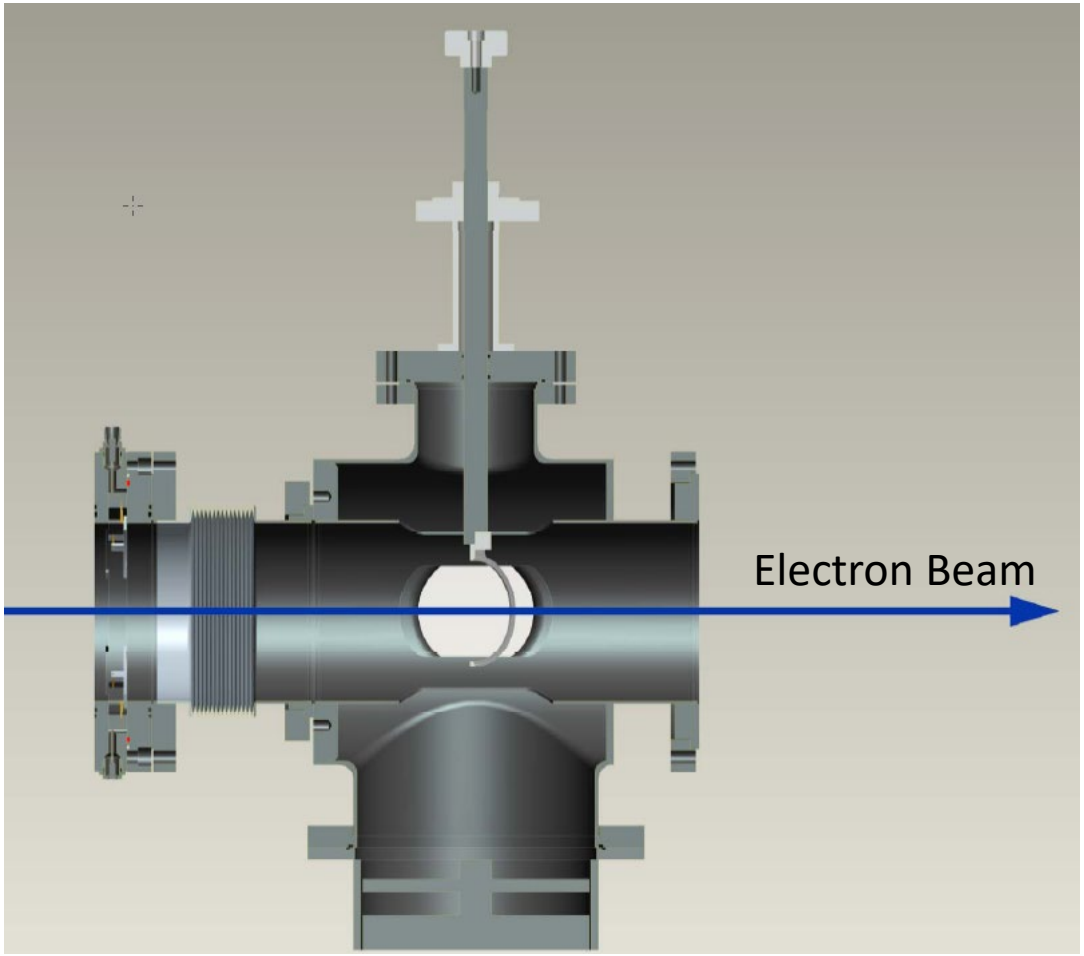


Time Resolved Beam Energy at the Exit of the Axis 1 Accelerator

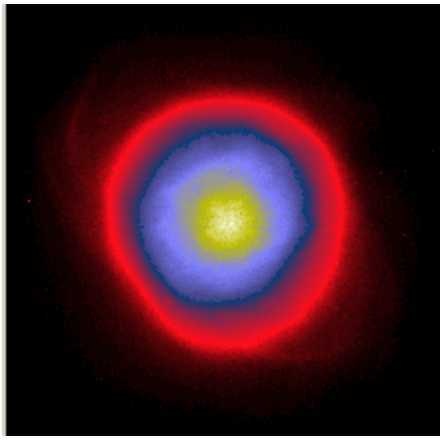


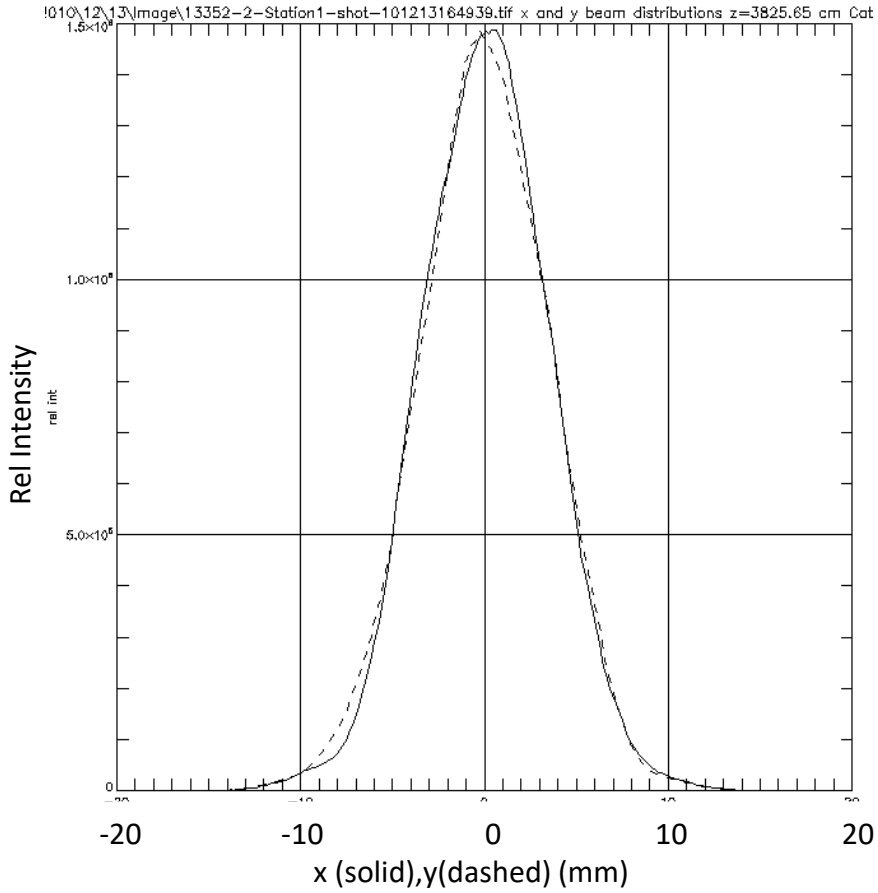


Experimental Configuration

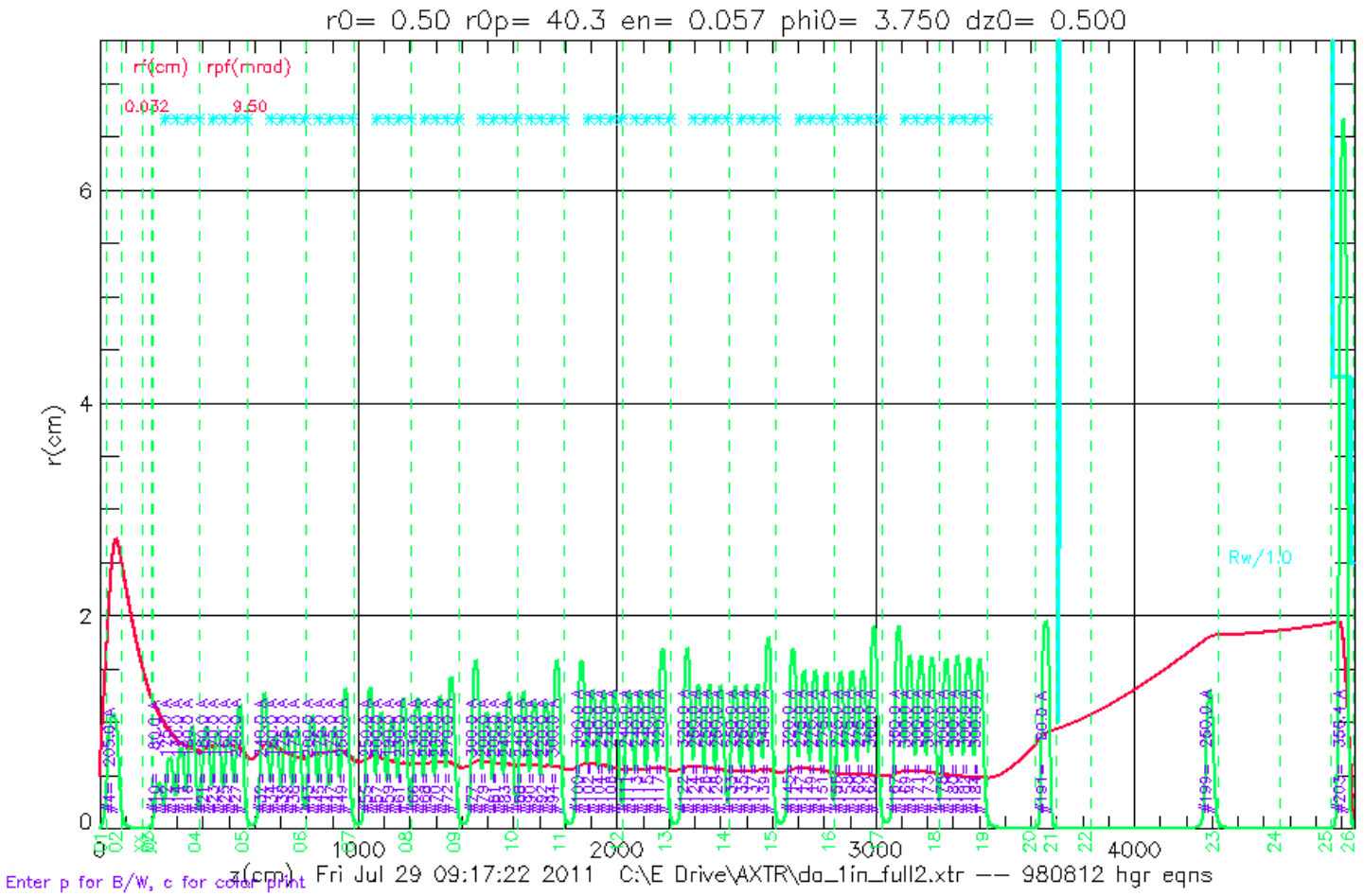


OTR Spatial Distribution with DT1 Current @ 180A, Z=3825.7cm from the 25mm Cathode

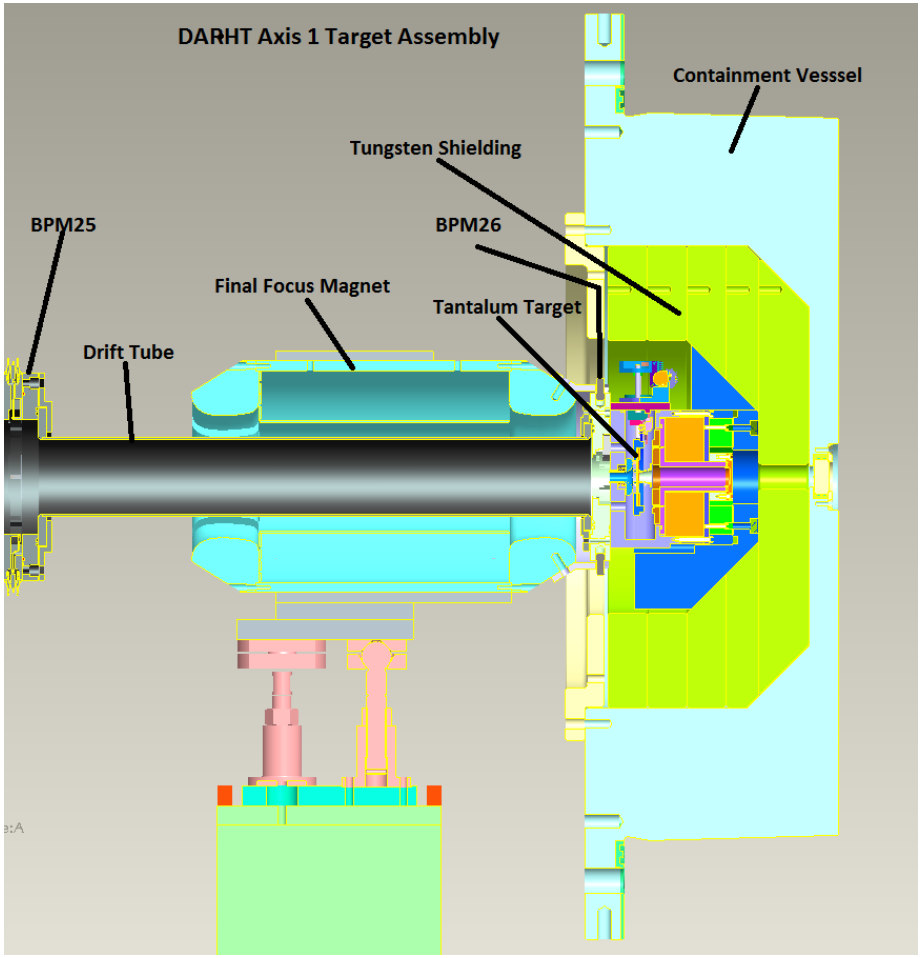




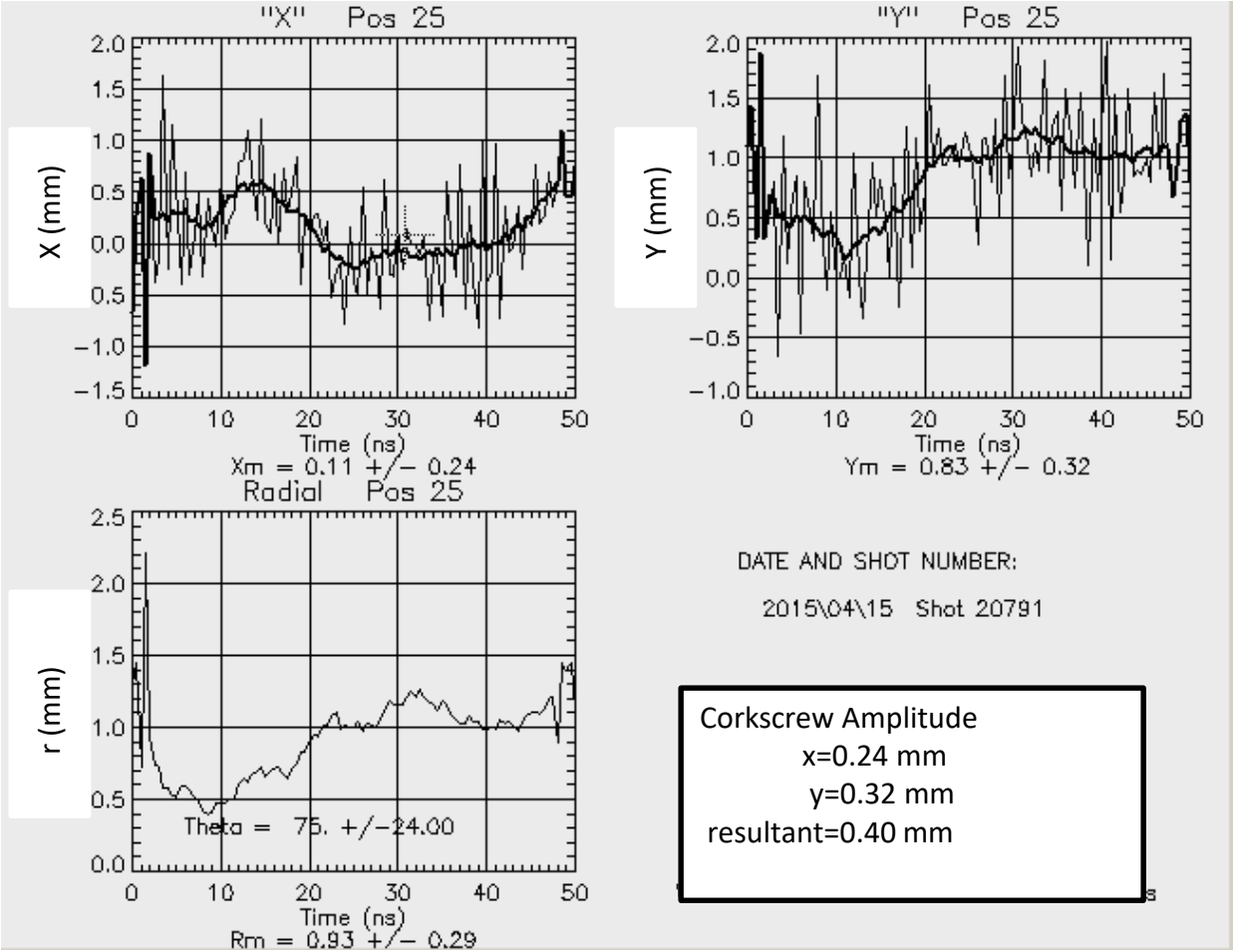
XTR Transport through the Entire Accelerator



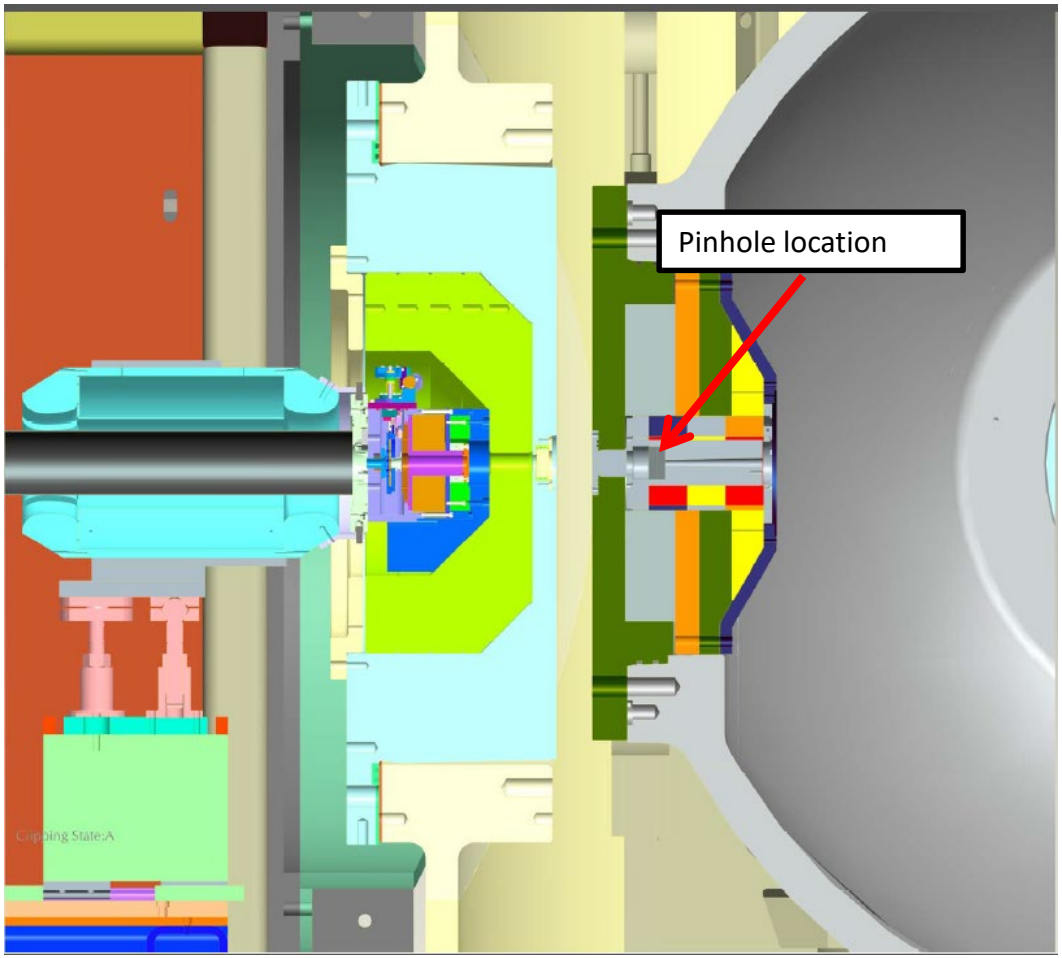
Final Focus Layout



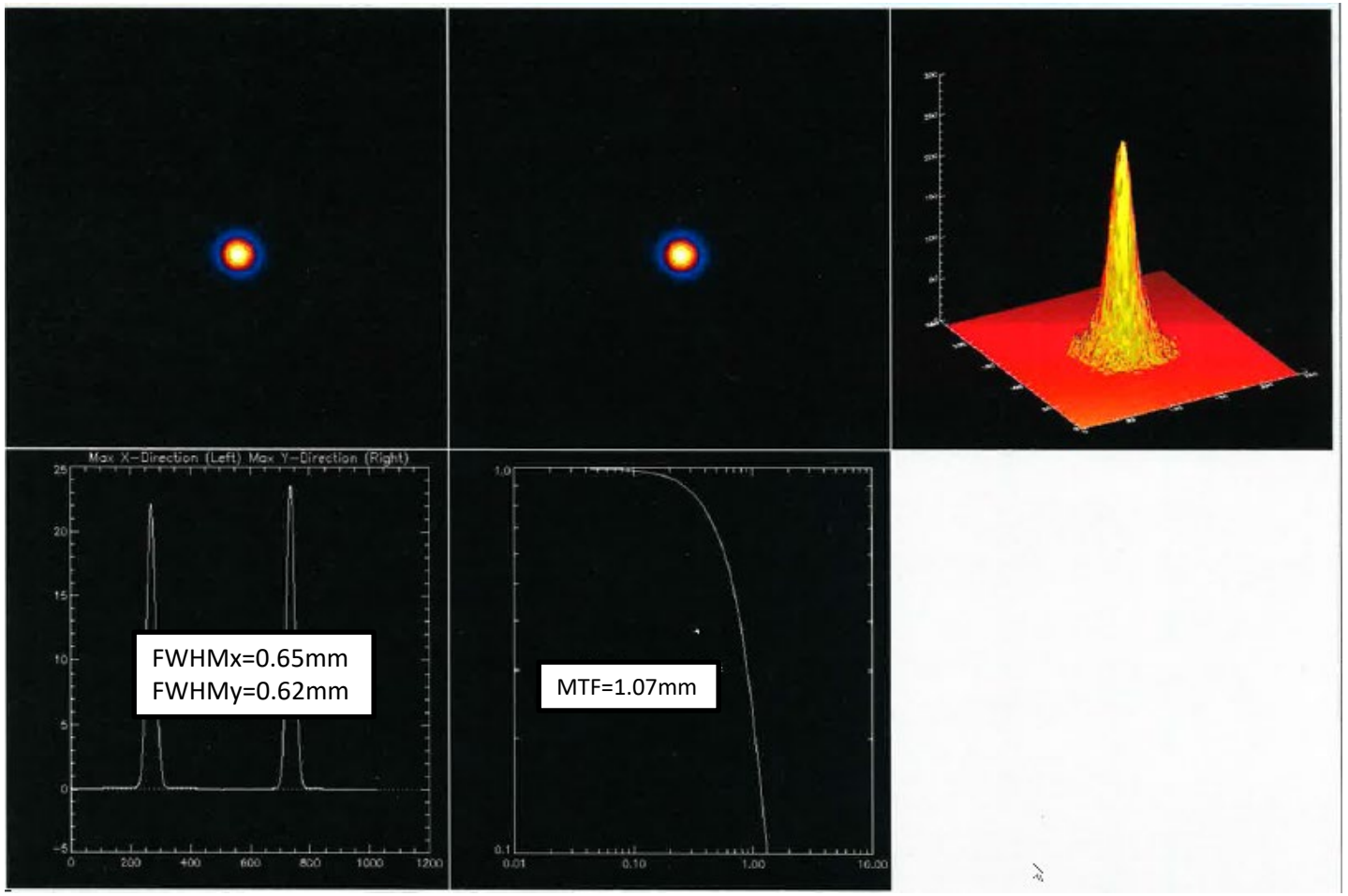
Corkscrew/BBU Amplitudes at BPM25



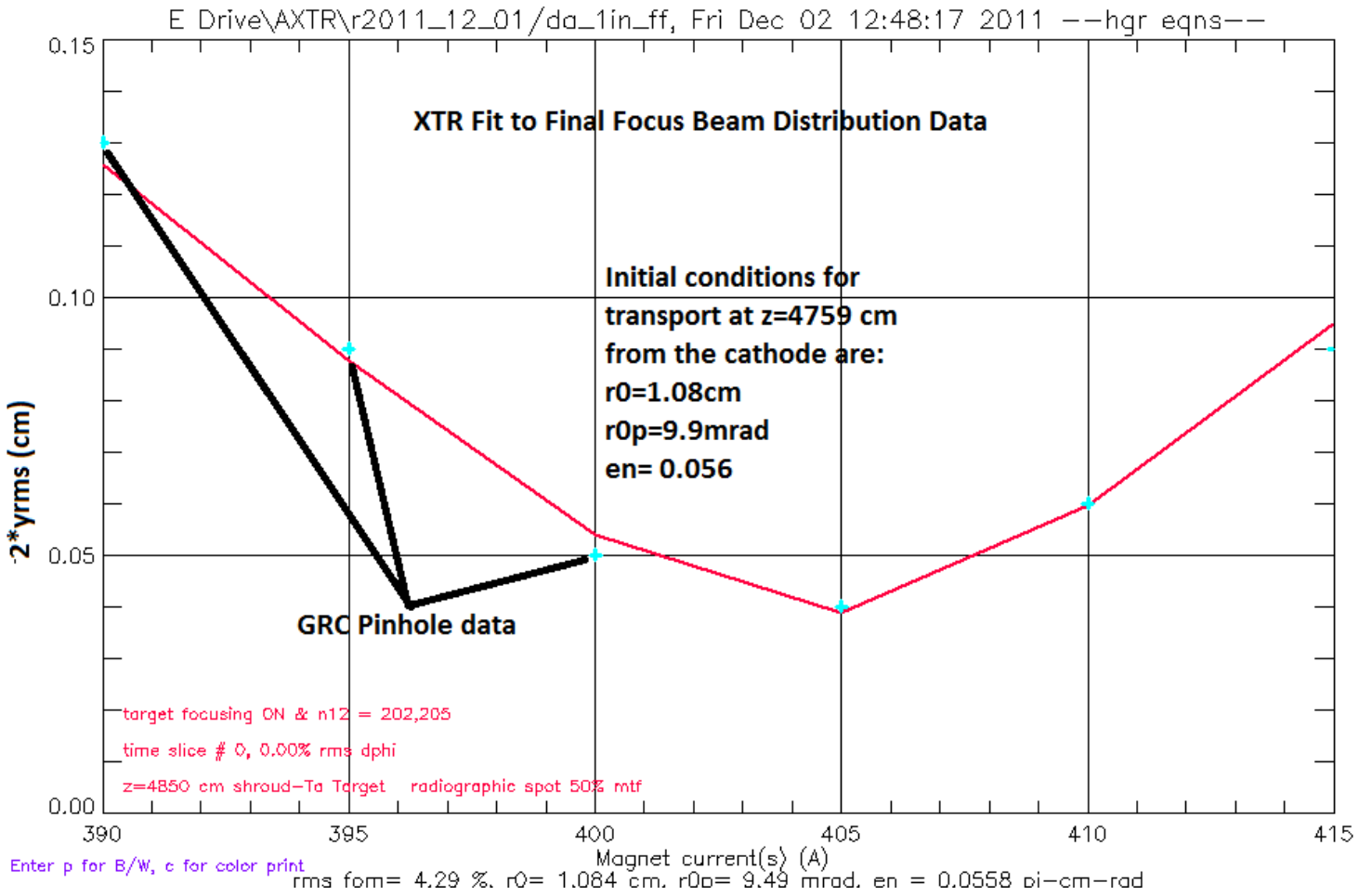
FF with Confinement Vessel



Typical GRC Pinhole Data for 50mm Cathode FF=405A 560R@1m



Sweep of FF Using GRC Pinhole Data 25mm Cathode



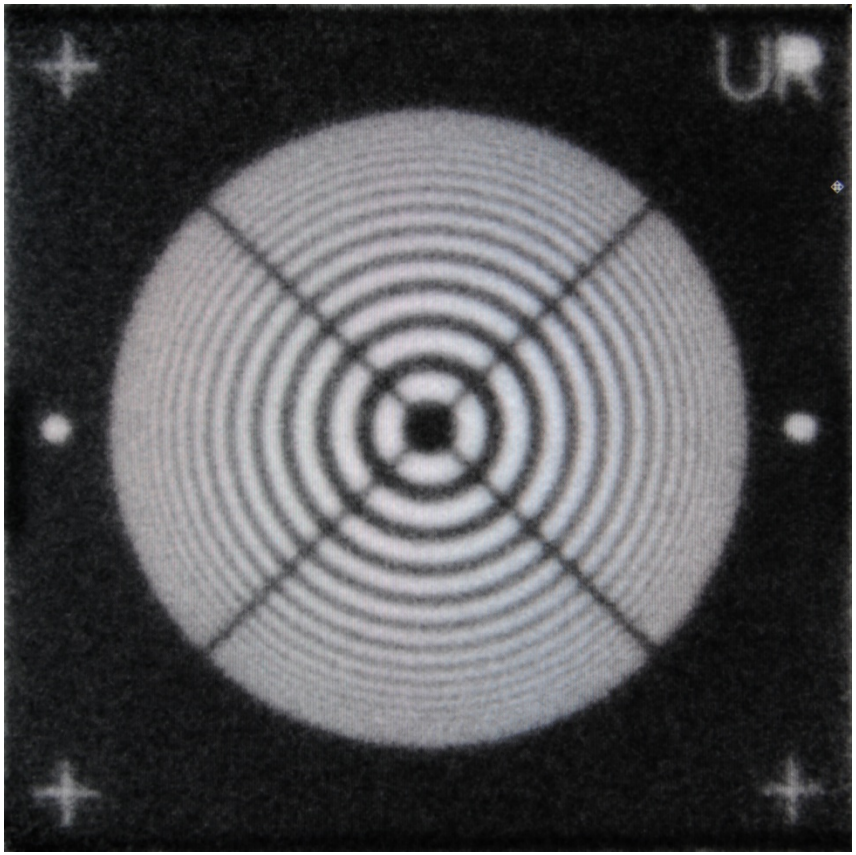
Axis 1 Variable Cathode Tuning

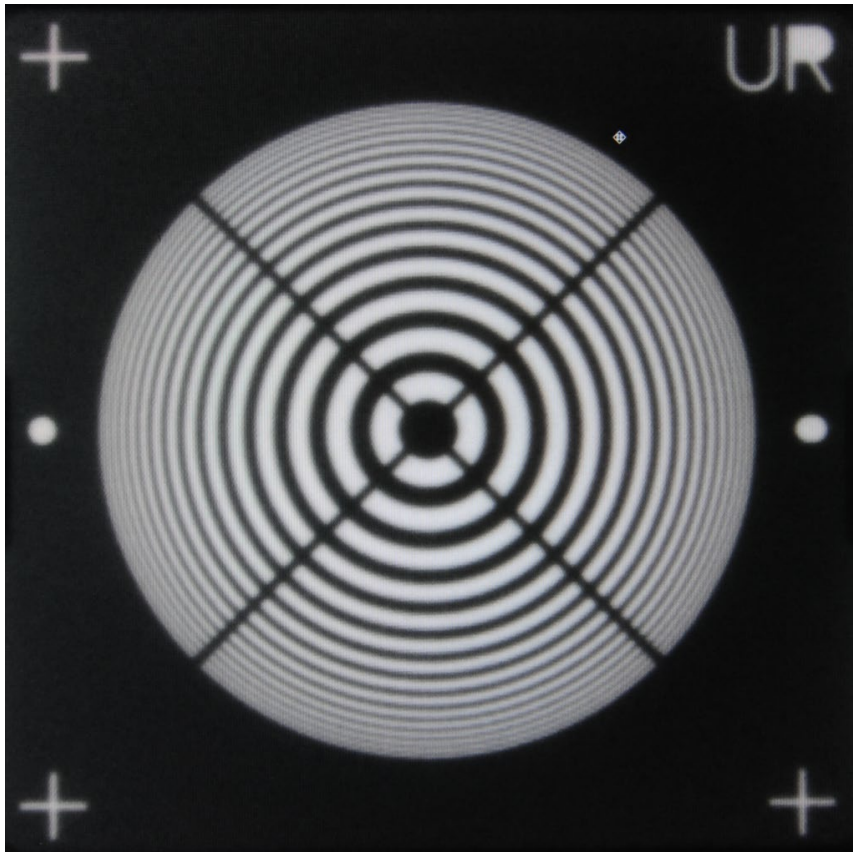
Parameter	2” Cathode	1” Cathode	3/4” Cathode	2.75” Cathode
Beam Energy	19.4	19.4	19.6(19.1)	19.1
Beam Current	1.8kA	460 A	250 A (210)	2.9 kA
Injector Charge V Injection Energy	112 kV 3.72MeV	112 kV 3.75kV	112 kV (98) 3.79MeV (3.35)	112 kV 3.70MeV
Spot Size (50%MTF)	0.95 mm	850 µm	690 µm (650)	2.0 mm
Dose@1m (1.0mm Ta)	568 R **	145R*	81 R (63)*	878 R*
Dose@1m (0.1mm Ta)			(42)+	

* All values except 2” cathode are scaled by c*Q*V^2.8
**Referenced to Platinum Calorimeter
+ Relative measurement from GRC

Additional dose variations are possible by adjusting the Injector Charge Voltage.

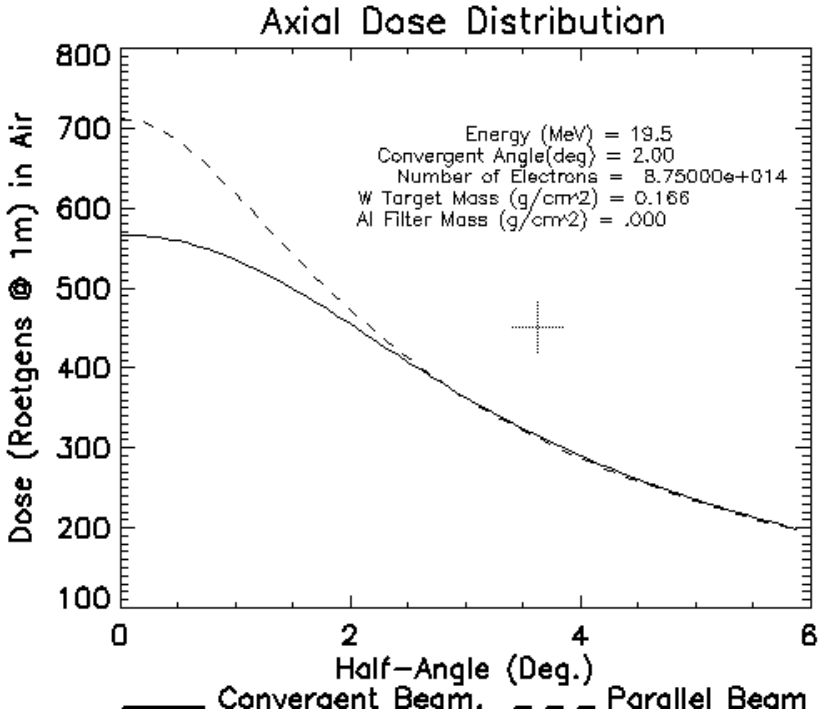
2’’ Cathode vs 1” Cathode

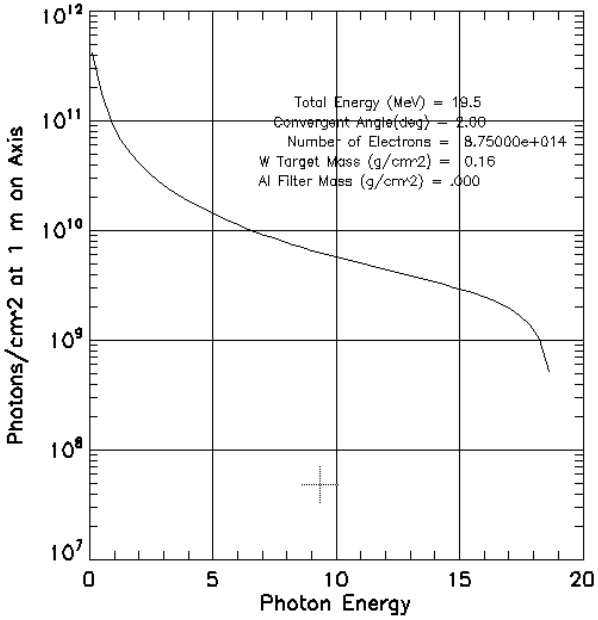




Resolution Range: 2.3mm – 250 µm

Calculations of Dose and On- Axis Bremsstrahlung for 50mm Cathode using Dosecalc





Operational Sequence for Hydro Shot using Axis 1

- Two weeks prior to shot week
- Dose specified by experimenter and cathode size determined.
- Cathode installed and conditioned (1-2 days)
- Machine tuned (steering to BPM25) pulse power timing optimized (1/2 day)
- Sweep final focus for optimum spot (1/2day) accelerator settings fixed for hydro test.
- Shot number for the hydro test is identified and stored.
- One week prior to shot
- Align hardware in vessel
- Perform shot related statics and timing runs
- Shot week
- Pre-shot statics (flat fields, resolution targets, grid)
- Last hydro fired (H4275) 23 target shots

Weight of the Paper for Axis 1

- Over 100-Tech Notes
- Approximately 50-Procedures, IWD's, Training, Plans and Safety Basis Documents (some are common to both Axis 1 and 2)

Conclusions

- Axis 1 is reproducible week to week for shot sequence with a given cathode.
- Accelerator has operated for 50 hydro tests since November 2000
- For hydro tests accelerator is operated by one accelerator operator (AO) and one operations supervisor (OS).
- During operations, OS is capable of identifying problems using analysis code.